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AN OCEAN WAVE MEASURING BUOY

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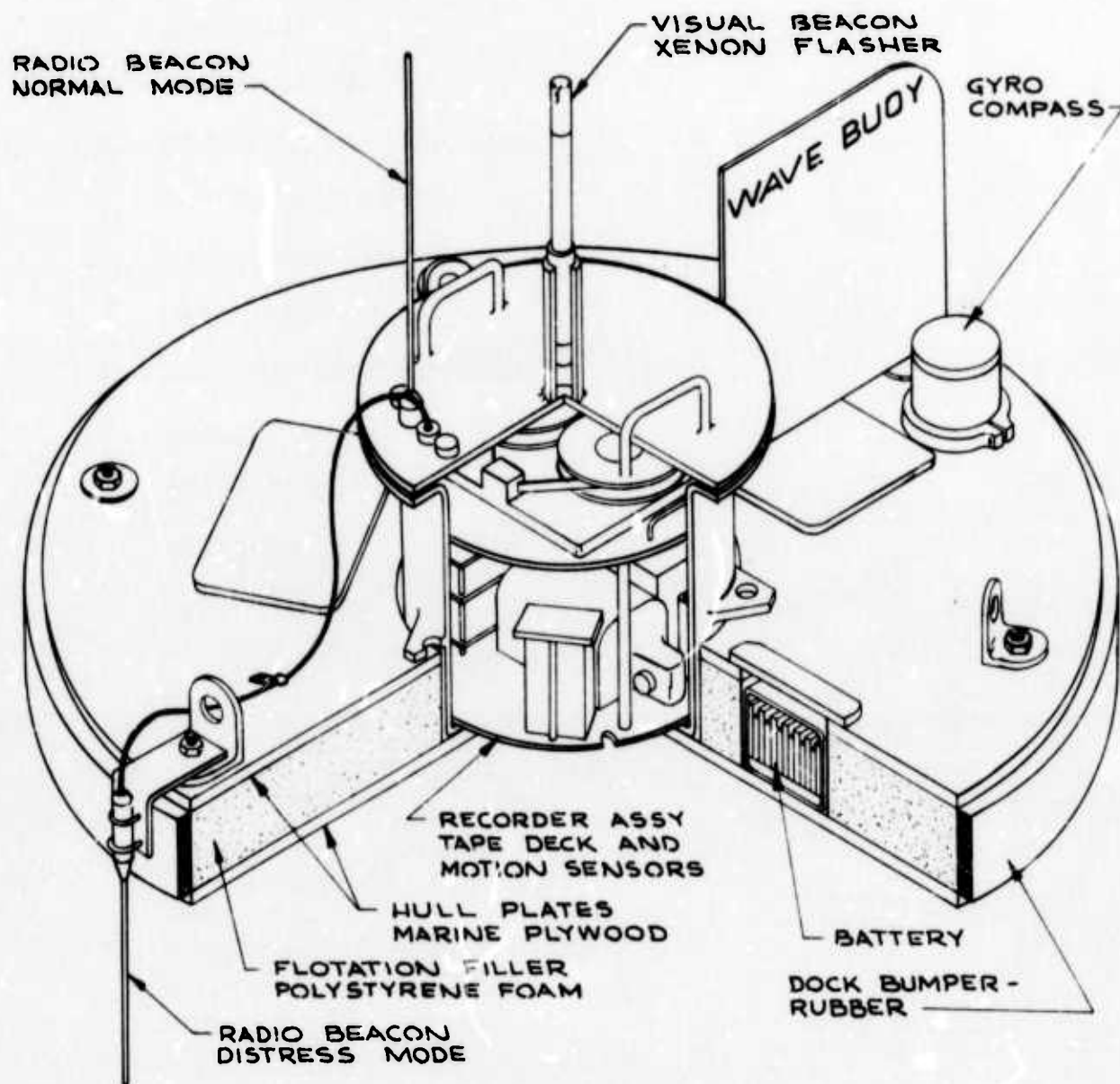
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# WAVE BUOY

CUTAWAY VIEW

FRONTISPIECE

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## TABLE OF CONTENTS

	Page
ABSTRACT	1
1. INTRODUCTION	1
2. PRINCIPLE OF OPERATION	3
3. DESIGN PARAMETERS	7
4. BUOY CONSTRUCTION	10
5. DATA ANALYSIS	22
6. BUOY RESPONSE TO WAVES	25
7. CONCLUSION	31
REFERENCES	36
APPENDIX	38

## AN OCEAN WAVE MEASURING BUOY

### ABSTRACT

We describe the design, construction, and performance of a surface wave-following buoy that can measure the directional spectrum of 0.06 to 0.5 Hz ocean waves with an accuracy of 10%, and an angular resolution of around 90°. The buoy is disc shaped, 1.5 m (5 feet) in diameter, weighs 150 kgm (300 lb), and is completely self-contained. Wave height is measured by an accelerometer mounted on the inner gimbal of a vertical gyro, wave slopes by the tilt of the buoy about the gyro's vertical axis, and buoy heading by a gyro stabilized compass. Data from the transducers are digitized and recorded on computer compatible magnetic tape. Wave spectra are calculated from the data by computer. The accuracy of the measurements is verified by calibration in a wave tank, and by the internal consistency of the data.

### 1. INTRODUCTION

The wave measuring buoy described in this report was designed to provide directional spectra of ocean waves for comparison with radar scatter data. Initially we sought to purchase a buoy, but a quick survey of available instruments showed that none were capable of measuring a directional spectrum. Thus we were forced to design and construct one.

A number of techniques exist for determining the directional distribution of a wave field. Essentially, the measurement requires a coherent sample of the wave field over many wavelengths. The directional resolution is proportional to the number of wavelengths used. The measurement of the ocean wave field is particularly difficult because it is difficult to establish a fixed reference point to which wave heights can be related. Wave data can be measured at several places using an array on a stable platform, or, alternately, the surface elevation and two components of slope (tilt) can be measured at one point using an inertial reference.

A buoy that measures wave height and tilt (commonly called a pitch-and-roll buoy) is particularly simple, and can be small and easily handled. We have chosen this technique.

Several pitch-and-roll buoys have been built in the past. The first were designed and built by the National Institute of Oceanography in England. One was contained in a 5 feet 6 inch cast aluminum, ellipsoidal hull (Longuett-Higgins, Cartwright, and Smith, 1963). Later versions used 54" torus shaped hulls. Still later, another version was built by Hudson Laboratories of Columbia University (Saenger 1969a, b; Goldberg and Goldberg, 1969; Jordan, 1969). All of these buoys required a ship to stand by for recording data and supplying power. Our design borrows heavily from these previous instruments and is an

extension of their concept: It is completely self contained and can operate unattended.

## 2. PRINCIPLE OF OPERATION

The hull of a pitch-and-roll wave measuring buoy is disc shaped, of shallow draft, and is radially symmetric about an axis normal to the water surface. Such a hull will follow the surface of a wave provided the wavelength is sufficiently long; and its high frequency response will be independent of wave direction. The buoy contains an accelerometer mounted on the axis of a vertical gyro and a gyro stabilized compass. The vertical component of acceleration, when doubly integrated, gives the sea surface height. The buoy tilts, when referenced to the vertical axis of the gyro and to the compass heading, gives the wave slopes in a fixed (North centered) coordinate system. These variables can be related to the ocean-wave directional spectrum and its lower-order moments.

Let

$$(\zeta_1, \zeta_2, \zeta_3) = (\zeta, \partial\zeta/\partial x, \partial\zeta/\partial y) \quad (2.1)$$

be the wave height and slopes measured by the buoy as a function of time in a coordinate system with  $x, y$  pointing North and East (Fig. 1b). The spectrum  $F_i(k_x, k_y)$  of  $\zeta_i(x, y, t_0)$  at some instant  $t_0$  is so defined that

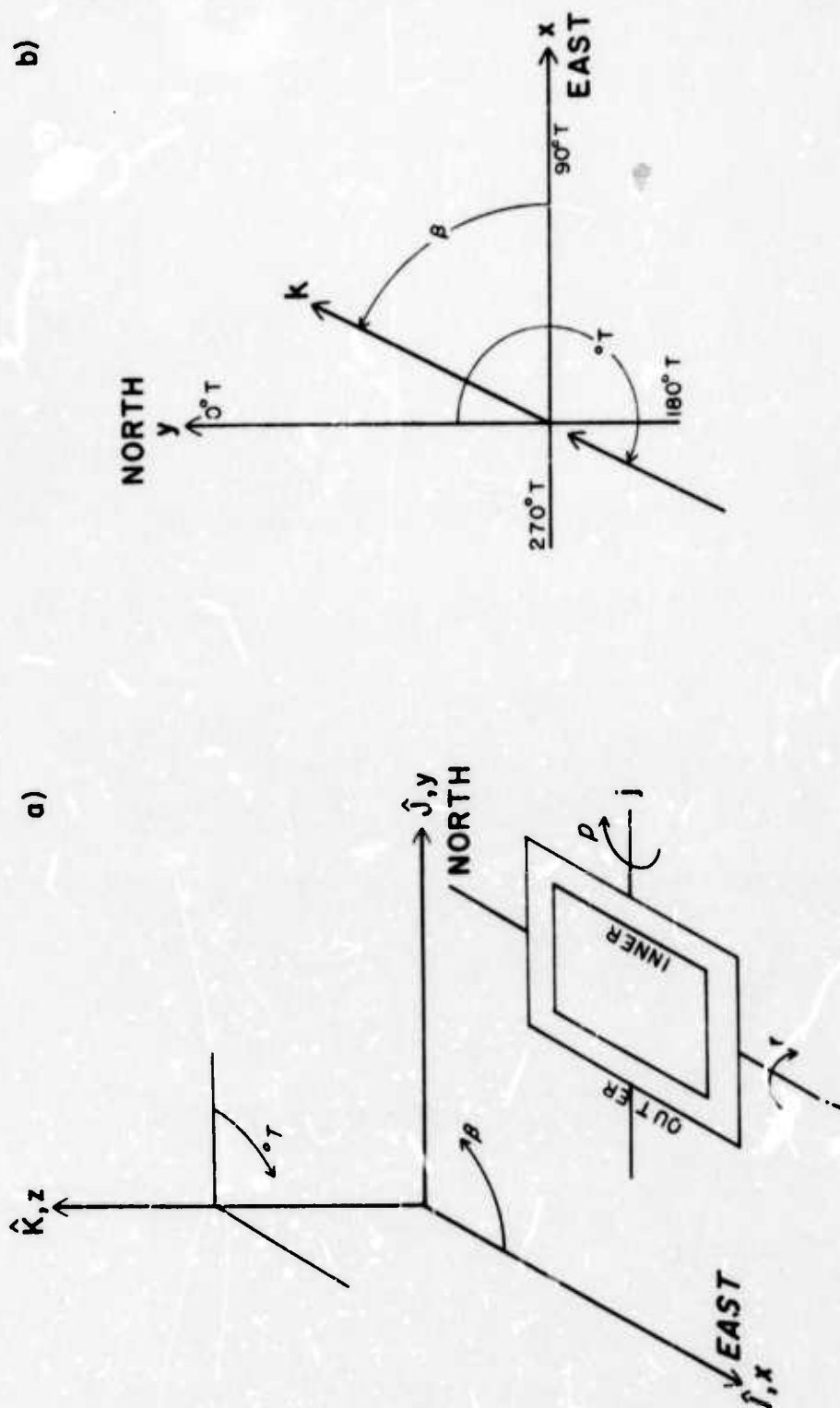


Figure 1. Coordinate system: a) of vertical gyro, b) for analysis of data.

$$\begin{aligned} \langle \zeta_i^2 \rangle_{\text{space}} &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_i(k_x, k_y) dk_x dk_y = \\ &= \int_0^{\infty} \int_0^{2\pi} F_i(k, \beta) k dk d\beta . \end{aligned} \quad (2.2)$$

Similarly, for time series  $\zeta_i(x, y; t)$  at one point  $x_0 y_0$ ,

$$\langle \zeta_i^2 \rangle_{\text{time}} = \int_0^{\infty} \int_0^{2\pi} F_i(\omega, \beta) d\omega d\beta , \quad (2.3)$$

where  $\omega$  is a radian frequency,  $k$  is the wave number.

By the ergodic theorem the space and time averages can be equated:

$$F_i(\omega, \beta) d\omega = F_i(k, \beta) k dk . \quad (2.4)$$

For deep-water waves,  $\omega^2 = gk$ , where  $g$  is the acceleration of gravity, and the required Jacobian is

$$J = \frac{F_i(k, \beta)}{F_i(\omega, \beta)} = \frac{1}{k} \frac{d}{dk} = \frac{g^2}{2\omega^3} . \quad (2.5)$$

It is convenient to express all measured spectra in terms of  $F_i(k_x, k_y)$ ,  $F_i(\omega, \beta)$ , etc., e.g. the contributions (per unit wavenumber space, per unit frequency-radian, etc.) to the mean-square surface elevation. We omit the subscript "i" and refer to  $F( )$  as simply the wave spectrum.

The Cartesian moments are written

$$\begin{aligned} M_{pq} &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k_x^p k_y^q F(k_x, k_y) dk_x dk_y = \\ &= \int_0^{\infty} k^{p+q} N_{pq}(k) k dk \end{aligned} \quad (2.6)$$

where

$$N_{pq}(k) = \int_0^{2\pi} \cos^p \beta \sin^q \beta F(k, \beta) d\beta. \quad (2.7)$$

For an elementary wave train, the wave height and slope are

$$\begin{aligned} \zeta_1 &= \xi = R e^{i(k \cdot x - \omega t)} \\ \zeta_2 &= \partial_x \xi = R i k \cos \beta e^{i(k \cdot x - \omega t)} \\ \zeta_3 &= \partial_y \xi = R i k \sin \beta e^{i(k \cdot x - \omega t)}. \end{aligned} \quad (2.8)$$

The co-spectra  $C_{ij}$  and quadrature-spectra  $Q_{ij}$  of any pair of quantities  $\zeta_i$  and  $\zeta_j$  can be expressed in terms of the moments:

$$C_{11}(\omega) = \int_0^{2\pi} F(\omega, \beta) d\beta = J^{-1} N_{00} \quad (2.9)$$

$$C_{22}(\omega) = \int_0^{2\pi} k^2 \cos^2 \beta F(\omega, \beta) d\beta = J^{-1} k^2 N_{20}$$

$$C_{33}(\omega) = \int_0^{2\pi} k^2 \sin^2 \beta F(\omega, \beta) d\beta = J^{-1} k^2 N_{02}$$

$$C_{23} = \int_0^{2\pi} k^2 \cos \beta \sin \beta F(\omega, \beta) d\beta = J^{-1} k^2 N_{11}$$

$$Q_{12} = \int_0^{2\pi} k \cos \beta F(\omega, \beta) d\beta = J^{-1} k N_{10}$$

$$Q_{13} = \int_0^{2\pi} k \sin \beta F(\omega, \beta) d\beta = J^{-1} k N_{01}$$

$$\text{and } C_{12} = 0, C_{13} = 0, Q_{23} = 0. \quad (2.10)$$

Furthermore, a trigonometric identity gives

$$k^2 C_{11} = C_{22} + C_{33} \quad (2.11)$$

Equations (10) and (11) serve to estimate the accuracy of the buoy data.

The five moments determined by the buoy can serve to evaluate the first five Fourier terms of the directional distribution of ocean-wave energy (at each frequency)

$$F^{(5)}(k, \beta) = 1/2 a_0 + a_1 \cos \beta + b_1 \sin \beta + a_2 \cos 2\beta + b_2 \sin 2\beta$$

with

$$(a_0, a_1, b_1, a_2, b_2) = (N_{00}, N_{10}, N_{01}, N_{20}, -N_{02}, 2N_{11}) \quad (2.12)$$

The terminated Fourier expansion can be expressed in the form (Longuet-Higgins, Cartwright, and Smith, 1963)

$$\bar{F}^{(5)}(k, \beta) = \frac{1}{2\pi} \int_0^{2\pi} F(k, \beta) W(\beta' - \beta) d\beta' \quad (2.13)$$

where  $W = 1 + 2\cos(\beta' - \beta) + 2\cos 2(\beta' - \beta)$  can be regarded as a weighting function associated with the buoy measurements. When  $\beta' - \beta = 0, \pm 44^\circ$ ,  $W = 5, 5/2$  respectively. Thus the angular resolution of the tilt buoy can be taken at  $88^\circ$ . This is not very good, but it is the penalty one must pay for having a simple instrument.

### 3. DESIGN PARAMETERS

The wave buoy was to be used primarily in a trade-wind sea. To meet our requirements it must measure the ocean wave spectrum in the frequency band of 0.06 to 0.5 Hz (2-16 sec period) while wind speeds range up to 15 m/sec. Furthermore, it must be completely self-contained and operate for up to 24 hours unattended.

Typically, we expect to place it in operation and then conduct other experiments nearby. After three or four hours we would return and recover the buoy. The measured spectra should have an error of no more than 10% in amplitude or  $10^\circ$  in direction. These criteria determine the buoy size and transducer accuracy.

To estimate the accuracy required of the transducers using these criteria we assume an ocean wave spectrum proposed by Pierson and Moskowitz (1964)

$$S(\omega) = (\alpha g^2 \omega^{-5}) \exp[-\beta g^4 (v\omega)^{-4}] \quad (3.1)$$

where

$$S(\omega) = \int_0^{2\pi} F(\omega, \beta) d\beta$$

and  $v$  is the mean wind velocity. We use  $\alpha = 8.1 \times 10^{-3}$  and  $\beta = 0.74$ . The acceleration spectrum derived from (3.1) is:

$$S_A(\omega) = \alpha g^2 \omega^{-1} \exp[-\beta g^4 (v\omega)^{-4}] \quad (3.2)$$

The root-mean-square accélération is:

$$\langle \zeta_A \rangle^{1/2} = \left( \int_0^\infty S_A(\omega) d\omega \right)^{1/2} \quad (3.3)$$

This integral diverges because of the contributions at large  $\omega$ . However, a buoy will respond only to waves whose frequency is less than some frequency,  $\Omega$ ; its acceleration is found by integrating (3.3) to this upper limit. This gives:

$$\langle \zeta_A \rangle^{1/2} = (-\alpha g^2 / 4 E_1[-\beta g^4 (v\Omega)^{-4}])^{1/2} \quad (3.4)$$

Here  $E_i$  is the logarithmic integral defined by Jahnke and Emde (1945, p. 1). We expect the buoy to respond to waves whose wavelength is roughly twice the buoy diameter or greater (see the end of this section). Waves at the high frequency cut-off typically have a frequency of one Hertz. Letting  $\Omega = 2\pi/\text{sec}$ ,  $\langle \zeta_A \rangle^{1/2} = 13\% \text{ g}$  when  $v = 15 \text{ m/sec}$  and  $5\% \text{ g}$  when  $v = 2 \text{ m/sec}$ . To measure these accelerations with an accuracy of 10% requires an accelerometer with a total error band of less than 0.5% g over a range of 0-2 g.

The directional spectrum (2.12) is calculated from the slope spectra and co-spectra. The accuracy is limited mainly by the coefficients  $a_2$  and  $b_2$  which depend on the two slope measurements. Each must be measured to an accuracy of  $10\% + \sqrt{2}$  if the two components, taken together, are to have a total error of less than 10% on average.

The root-mean-square slope is directly related to the acceleration spectrum through the dispersion relation:

$$\langle \zeta_2^2 + \zeta_3^2 \rangle = k^2 \langle \zeta_1^2 \rangle = g^{-2} \langle \zeta_A^2 \rangle \quad (3.5)$$

The acceleration measured in units of g is the slope in radians. A 2 m/sec wind gives an RMS surface slope of  $3^\circ$ , a 15 m/sec wind gives  $7^\circ$ . A vertical gyro capable of measuring these angles to an accuracy of 7% must have an error of less than  $0.2^\circ$  over the band  $\pm 30^\circ$ , the Stokes limit for a progressive wave of maximum amplitude.

The operation of the wave buoy requires a hull which accurately follows the water surface. One that is disc shaped and of shallow draft will perform well until the wavelength becomes less than about twice its own diameter. Since a 2 sec wave has a wavelength of 6.2 meters, the buoy should be somewhat smaller than three meters. On the other hand, it should be easily handled. As a compromise, we arbitrarily chose a hull 1.5 m (5 ft) in diameter, with a draft of about 8 cm. Such a buoy displaces 150 kgm. Hudson Laboratories' experience with smaller buoys indicated that a hull of this size will survive 15 m/sec winds with only a small chance of being upset (of course it would not be sunk).

We estimate the response of this size buoy hull from Kim (1966). From his figure 11, the half-power point in heave response occurs when  $a = R\omega^2 g^{-1} = 1.5$ ,  $R$  is the radius of the buoy (0.75 m). This occurs at a frequency of 0.7 Hz. In a similar manner, the half-power point in the pitch response occurs when  $a = 3.8$  (Kim's figure 12). This corresponds to a frequency of 1.0 Hz. The hull responds to wave slope slightly better than to wave height near the cut-off frequency. In either case, the response is within 10% of unity at frequencies of 0.5 Hz and lower, so the hull should meet our requirements.

#### 4. BUOY CONSTRUCTION

The buoy consists of four main systems: 1) the transducers, 2) the signal conditioning and recording system, 3)

safety and recovery system, and 4) the buoy hull that houses and supports this equipment. We will discuss each in order. The sources of supply and cost of equipment discussed below, together with detailed electrical schematics, are included in the appendix.

The transducers consist of a vertical gyro, an accelerometer mounted on the inner gimbal of the gyro, and a gyro stabilized magnetic compass.

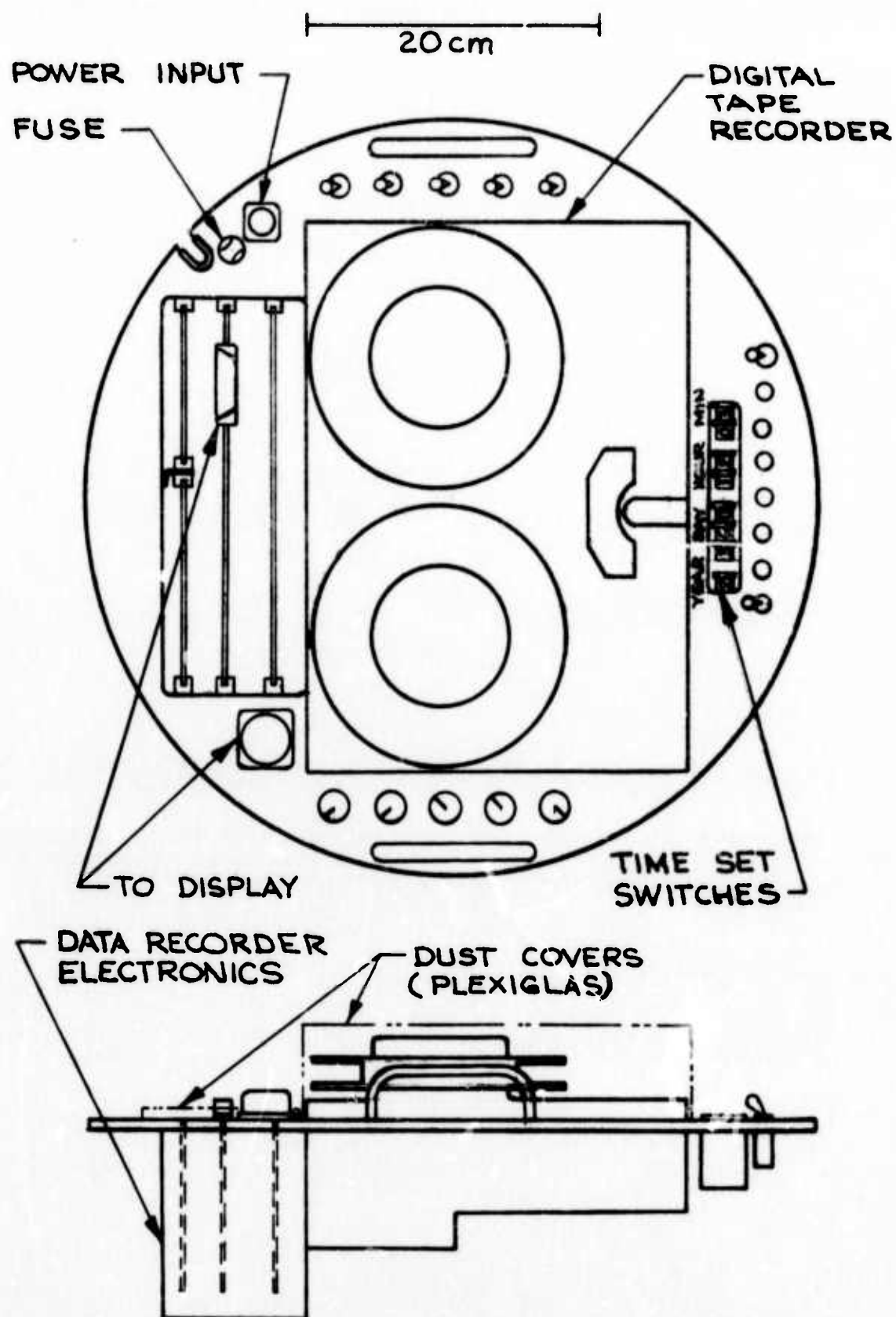
The gyro-accelerometer assembly was made by Honeywell, and consists of a vertical gyro (part number JG7044A45) and a quartz-fiber accelerometer (GG326C1). The accelerometer has a range of 0 to 2 g, a total error band of 0.01% g, a drift in sensitivity of 0.02% g/°C, and an zero point of  $4 \times 10^{-6}$  g/°C. The gyro gimbal remains vertical to within  $\pm 0.25^\circ$ , and has a full scale range of  $\pm 30^\circ$ . The tilt of the buoy is measured with a resistance potentiometer having a 1% linearity. The entire assembly is 26 x 15 x 14 cm in size, weighs 4 kgm, and uses about 50 watts of power.

Buoy heading is measured by a Humphrey North Seeking Gyro (DG04-0122-1). This consists of a gyro stabilized and gimballed magnet whose position is measured by a resistance potentiometer. The unit has an accuracy of  $\pm 1^\circ$ , and is linear within  $\pm 1\%$ . Physically, it is 21 x 8 x 8 cm, weighs 1 kgm, and uses 10 watts of power.

The recording system conditions the signals from the transducers, converts them to digital numbers, and records them on computer compatible magnetic tape. In addition, it controls the operation of the buoy, times its operation, and writes the time on the tape. The system was designed and built by Monitor Laboratories. The tape recorder is a standard unit manufactured by Precision Instruments (PI1387). The assembly is remarkably small (see figure 2), and its standby power requirement was less than two watts.

The signals from the transducers vary between  $\pm 5$  volts, and contain some noise at higher frequencies, particularly at 400 Hz (the frequency of the gyro supplies). To reduce aliasing errors, the signals are sent through low-pass filters. The voltages from the potentiometers (tilts and heading) go through a simple RC filter with a cut-off frequency of 20 Hz. The accelerometer signal is more severely attenuated since it must be integrated twice to obtain sea surface heights. Even a small amount of aliased power could cause severe errors in the measurement of low-frequency wave heights. This signal goes through a two-pole filter with a cut-off frequency of 1.0 Hz. The complex filter response functions are:

$$\begin{aligned} L &= (\omega^2 - 1)(\omega^4 + 1)^{-1} + j\sqrt{2} \omega(\omega^4 + 1)^{-1} \\ L &= (\omega^2 + 1)^{-1} + j\omega(\omega^2 + 1)^{-1} \end{aligned} \quad (4.1)$$



● LOW POWER DATA RECORDER ASSY ●

Figure 2.

where  $\omega$  is frequency in Hz. Measured responses are very close to values calculated from these equations: within 4% in amplitude and  $1/2^\circ$  in phase at the half-power frequency.

The filtered signals are multiplexed, converted to 12 bit binary numbers (an accuracy of approximately  $\pm 0.01\%$ ), and recorded on  $1/2$ " magnetic tape. The recording format is variable and controlled by switches. The correct time (year, day, hour, minute) is recorded at the beginning of each record. The time base was a quartz crystal having an accuracy of  $\pm 4$  seconds/day over a  $50^\circ\text{C}$  temperature range.

A 7 track, incremental tape recorder records the data at a density of 200 characters per inch and at a rate of up to 200 steps per second. It is rugged, can operate with 2 g RMS accelerations, uses one watt of power during standby and 40 watts while recording. The total amount of energy required to write 600 feet of tape is fixed at approximately 7 amp-hours from a 12 volt supply (72 joules). The rate of energy used is determined by the rate data is recorded. Typically, recording 144 bits/second uses 4 watts (144 bits/second = four 12-bit words, three times a second).

The recording system controls the buoy operation. The correct time is entered in the clock by switches. Once started, the system turns on power to the equipment 10 minutes before the next hour, and begins recording on the hour. Data are recorded in the format selected. After the selected amount has been written, recording stops and power is turned off. One,

two, or four hours later the cycle repeats, thus allowing the buoy to operate unattended for a number of hours.

Typically, each transducer is sampled 3.125 times/sec; 2048 samples are written in each record; and 16 records comprise a file. The records contain 10 minutes of data, the file about 3 hrs. Each file uses about 9 meters (27 feet) of tape. Spectra calculated from this data have a resolution of  $1.5 \times 10^{-3}$  Hz and a Nyquist frequency of 1.6 Hz. This format ensures that low frequency waves are adequately resolved, aliasing errors are small, and the time series are easily handled in the computer.

Power for the operation of the gyros and recording system comes from sealed, gel-cell, lead-acid batteries. In normal operation the buoy uses 7 amperes at 12 volts. Twenty-four hours of continuous operation requires 168 amp-hours of energy, but intermittent operation reduces this considerably. The buoy has six 20 amp-hour batteries. They operate in any position, and need not be protected from sea water. Each battery is isolated by diodes: failure of one does not affect the operation of the others. The batteries weigh 48 kgm and are a major part of the buoy weight, but are small in size ( $0.02 \text{ m}^3$ ).

The 12 VDC power is converted into other voltages required by the systems (see figure 3). The gyros operate from 115 and 26 VAC, 400 Hz. The first voltage is produced by a switched inverter (Nova). Switching transients occur on the 12 VDC lines and are reduced by the input and RF filters. The 26 VAC is derived from a transformer. A small amount of  $\pm 15$  and  $+5$

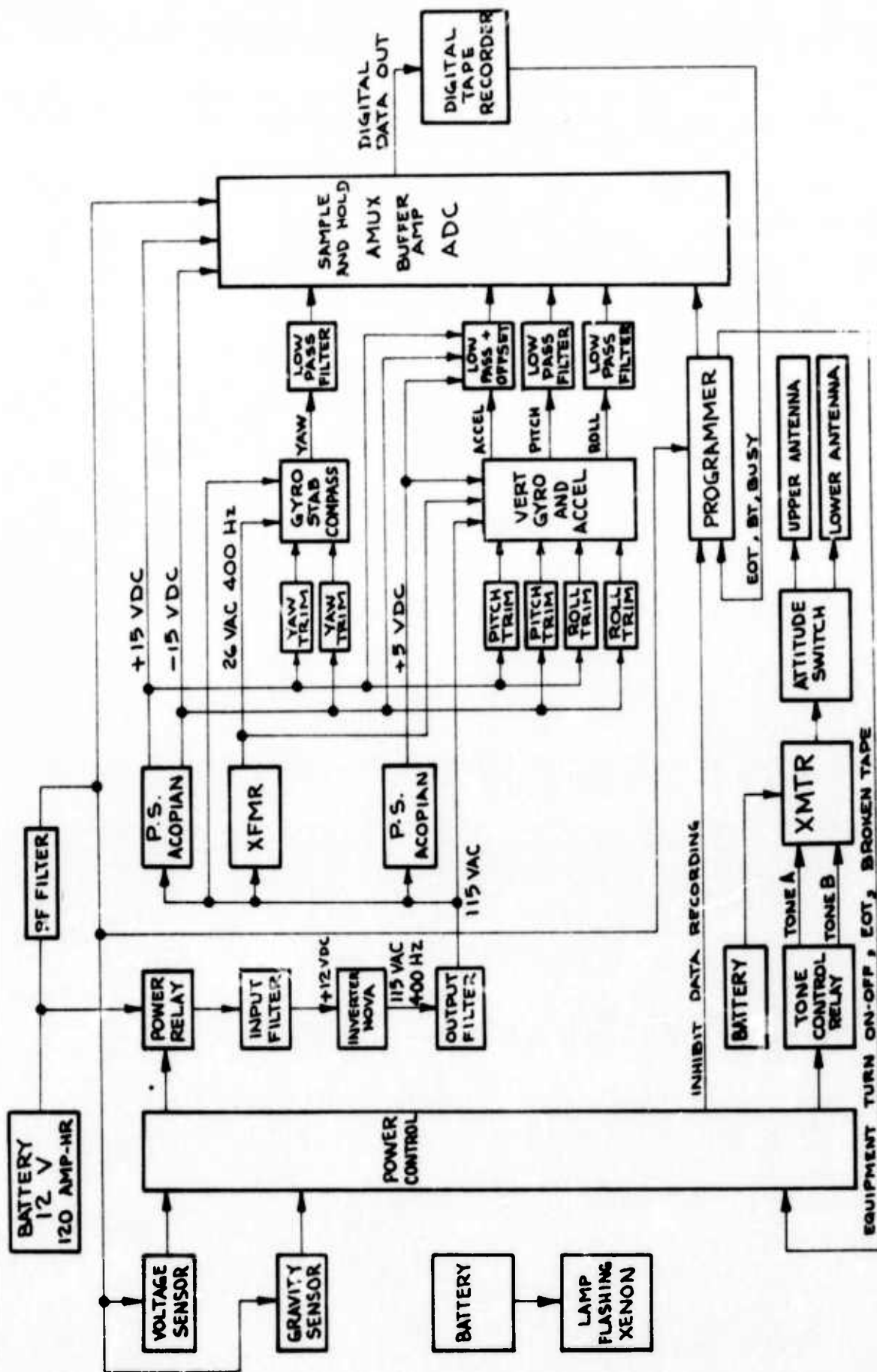


Figure 3.

VDC is produced by two Acopian power supplies. This serves the potentiometers, accelerometers, and data recorder.

The buoy is designed to operate unattended, consequently it has systems that help in finding it once it is out of sight. It also recognizes and responds to certain dangerous conditions such as overturning in large seas. In this event, the gyros tumble and no data can be obtained. Other mishaps include loss of power (batteries discharged), broken magnetic tape, or end of tape. The occurrence of any of these events turns off the power to the gyros, terminates the recording of data, and causes the buoy to call for help on its radio.

To aid in finding the buoy, it is painted bright yellow, has a flashing xenon light, and a citizen band (27 MHz) radio transmitter. The buoy can be seen for several hundred meters in 2 meter seas. The flashing light can be seen for one kilometer at night. The radio can be heard from 10 km away. The transmitter sends out 500 m watt pulses and has two antennas, one on top and one on the bottom of the hull. In the event of a mishap the pulse rate doubles. If the buoy overturns, the bottom antenna is activated. The antennas are small (40 cm long) and are not likely to be damaged while the buoy is handled. Both the light and the radio have their own batteries; both can operate for two days.

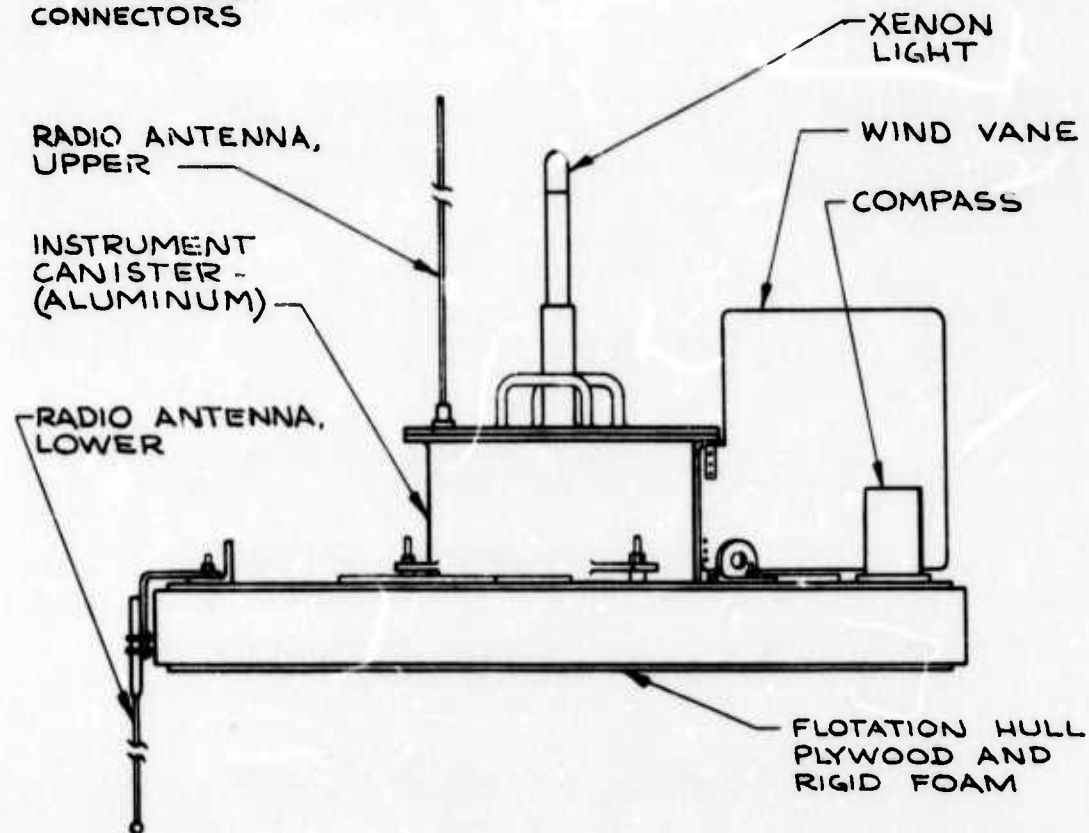
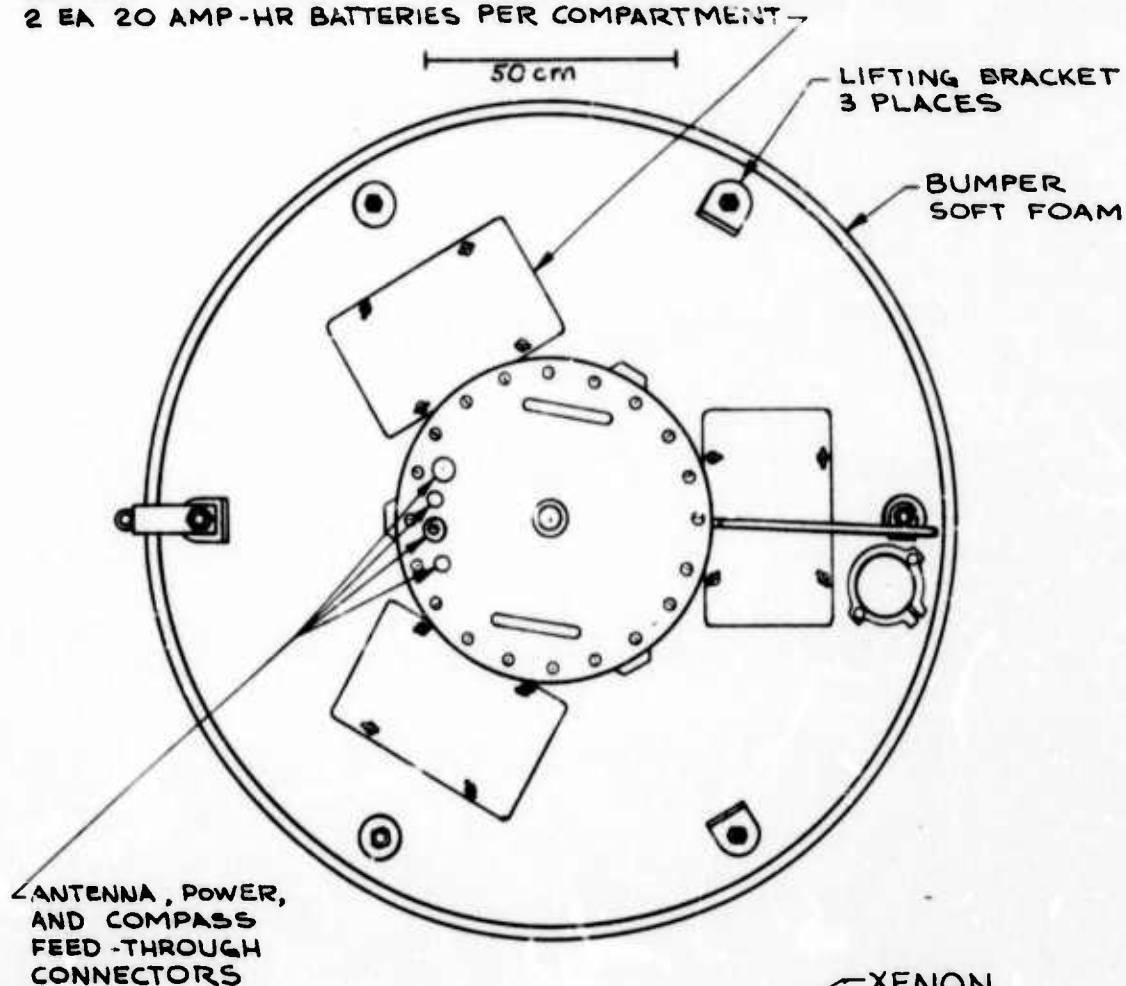
In typical operation, the buoy is started, and placed in the water. Some time later it starts and data is recorded. It

is difficult to stand around hoping all is well. To alleviate distress in the operators, the buoy has a small (100 m watt) citizen-band radio transmitter that transmits everything it hears. The operators, several hundred yards away can hear the gyros turn on and spin up, and can hear the tape recorder step each time data is recorded. This verifies that all is well, and the operators are relieved.

The general layout of the buoy hull is shown in the cut-away view (frontispiece) and figure 4. The control logic, vertical gyro, inverter, and transmitter are mounted together on a frame (figure 5). The data recorder (figure 2) mounts directly on top of this. The entire assembly is housed in a watertight aluminum can. The light and transmitting antenna are mounted on top of this. The north-seeking gyro (in a waterproof polyvinylchloride container) and the batteries mount on the buoy hull. Underwater type connectors connect them to the lid of the can. The container is 52 cm in diameter, 40 cm high, and weighs 60 kgm.

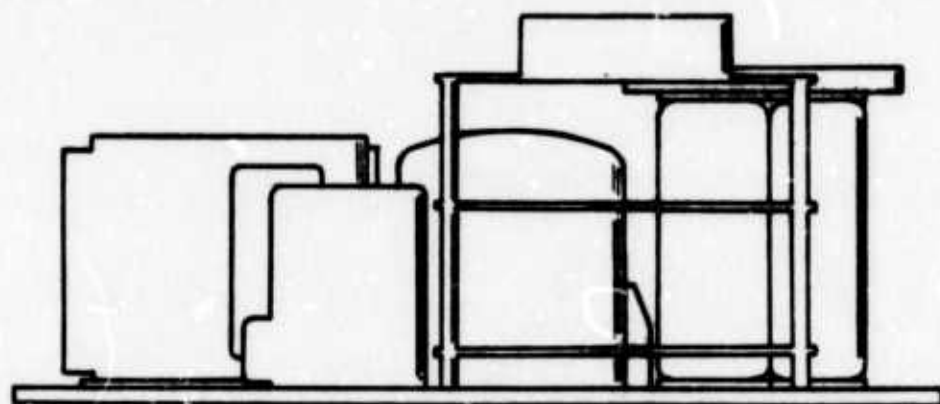
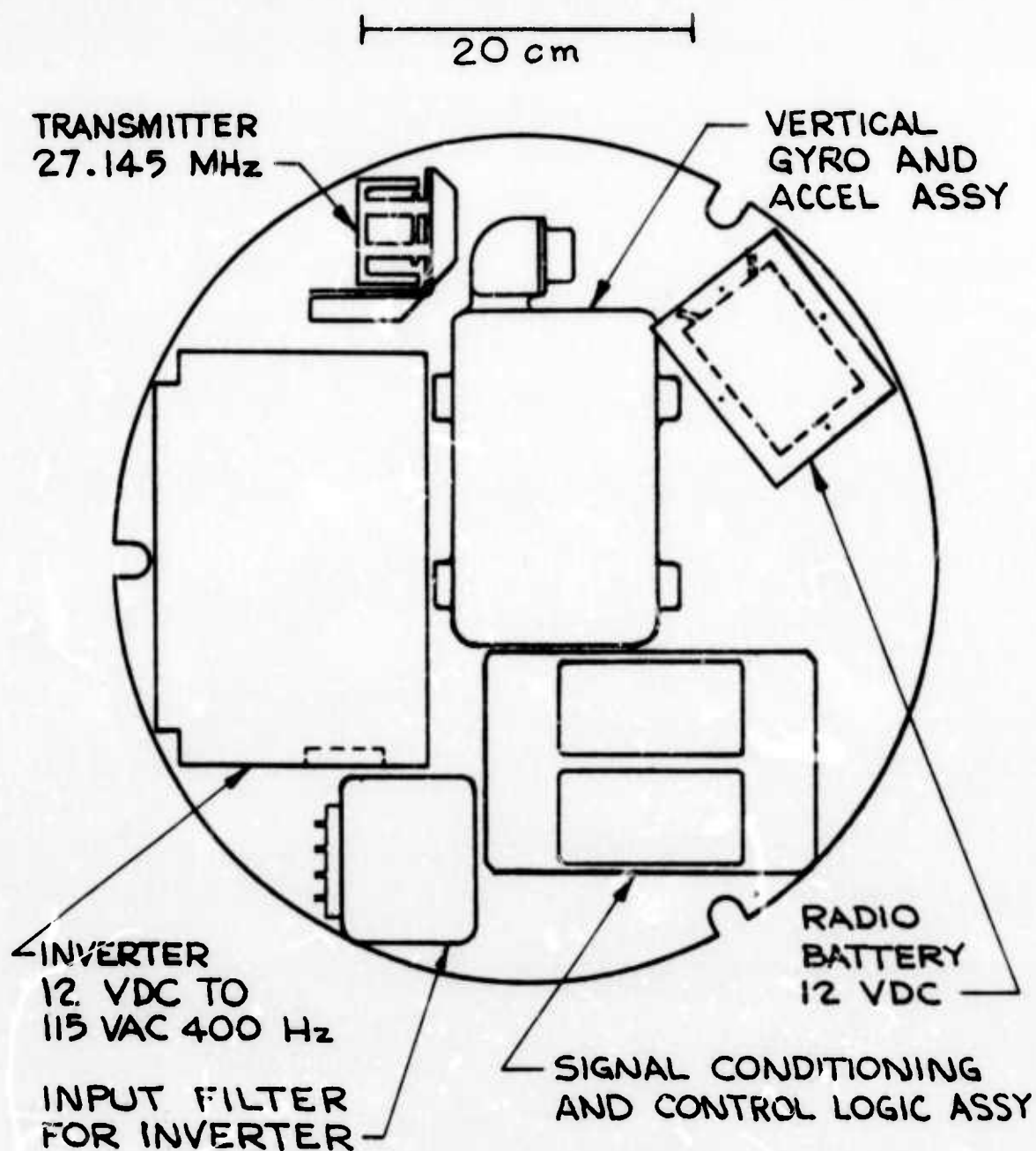
The hull is made of two, 1.5 meter (5 feet) diameter sheets of 1" marine plywood. Ten centimeters (4 in) of closed-cell styrofoam is sandwiched between them for floatation, and the three bolt together to form the hull. The aluminum can and gyro bolt into holes in the top piece of wood. The batteries are held below three hatch covers. All wiring is routed between the plywood sheets and protected. A small wind vane provides

BATTERY COMPARTMENT COVER (3 PLACES)  
2 EA 20 AMP-HR BATTERIES PER COMPARTMENT



● EXTERNAL BUOY CONFIGURATION ●

Figure 4.



• EQUIPMENT MOUNTING PLATE ASSY •

Figure 5.

further protection for the compass gyro. The edge of the hull has a soft neoprene bumper glued to the styrofoam.

The entire buoy assembly bolts together. The aluminum can is easily removed and carried into a protected laboratory for repairs, calibration, and setting switches for turning on the electronics. The electronic rack may be unplugged and removed. All electronic components, gyros, etc., plug in and can be removed for repair. Connections to the data recorder are by screws on a terminal strip. All internal wiring is laced together. Thus the entire assembly may be quickly and easily disassembled for repairs. In normal operation, the unit can be switched on, the lid to the aluminum can bolted on, the can bolted into the hull, and the buoy launched, all in 20 minutes, by three people.

A three-point bridle of spliced 3/4" nylon rope is attached to the buoy for launching. Usually, 30 meters of 3/4" polypropylene rope is attached to the bridle. When the buoy is in the water, this line floats on the surface upwind of the buoy. The heavy line is necessary to handle the buoy in rough seas. A smaller line (1/2") parted during one recovery.

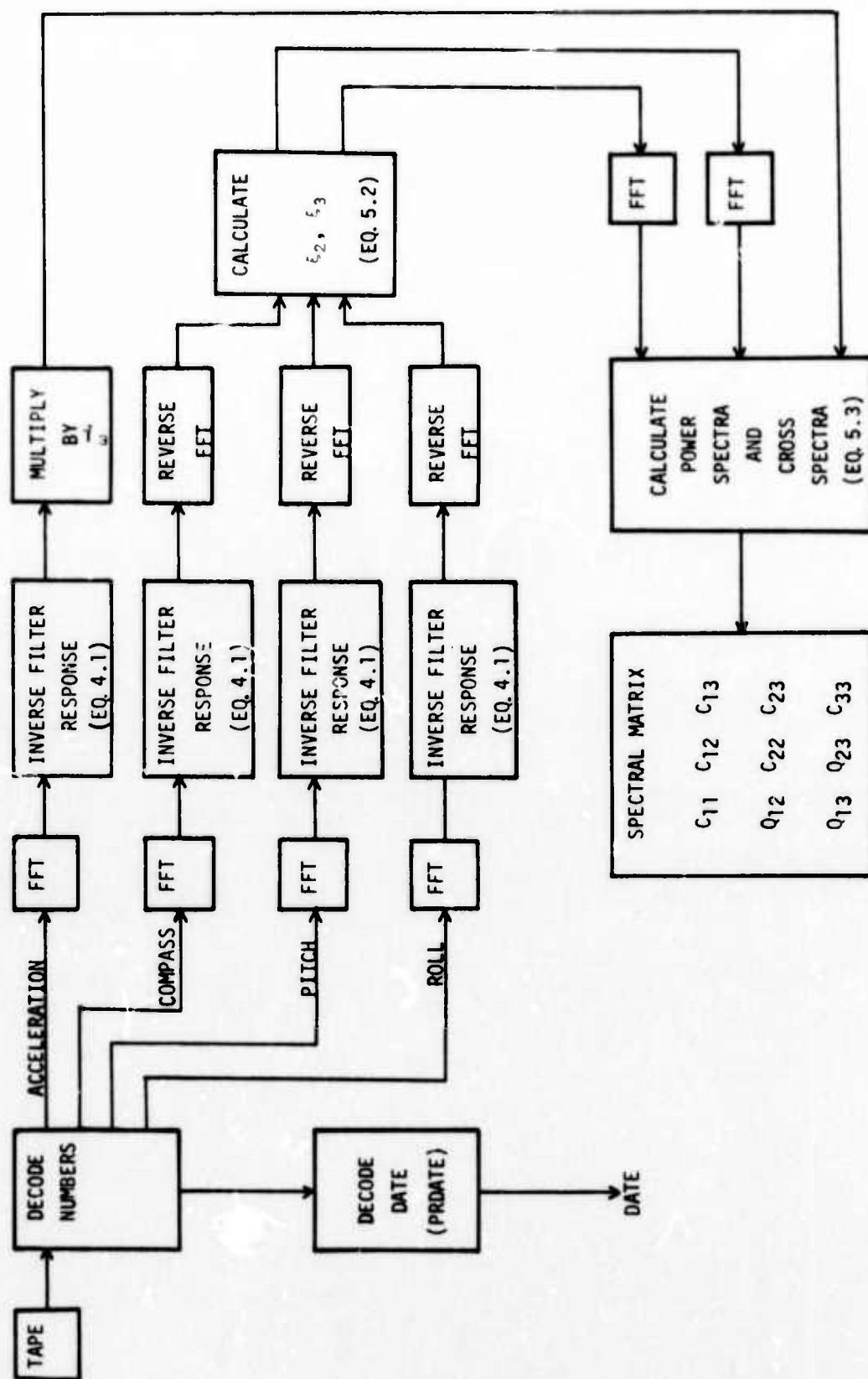
The aluminum can and wind vane are painted bright yellow (epoxy coating). The hull is bright red. English and Japanese lettering on the vane identifies the buoy. External fittings are stainless steel, external wiring is neoprene jacketed. This greatly reduces corrosion and electrical shorts to sea water.

## 5. DATA ANALYSIS

The buoy data are analysed on a Burroughs B6700 computer. A complete listing of the program is produced in the appendix. Although it appears long and complicated, it is, in fact, straightforward. Processing of data is quick, typically one hour of buoy data is analysed in 11 minutes at a cost of about \$25. The following paragraphs outline the procedure, shown graphically in figure 6.

Data from the four sensors (acceleration, two tilts, heading) are written on magnetic tape as six-bit characters. The first 24 bits of each record is a time word. The procedure TAPESTART positions the tape at the record to be read, and notes any read errors in records passed over. The procedure READTAPE transfers into the computer the bits written in a particular record, converts them into time series with appropriate units, removes the mean, and notes any apparent errors. Procedure PRDATE decodes the first 24 bits into time and date. The four time series are transformed into the frequency domain (using the Fast Fourier Transform) by the computer's library routines FFT and BITRV2.

The frequency data are multiplied by the appropriate inverse filter function  $L^{-1}$  calculated from (4.1). Some data were recorded with sample-and-hold modules installed in the data recorder. In this case, all channels were sampled simultaneously. Other data were recorded without the modules and the chan-



DATA ANALYSIS FLOW CHART

Figure 6.

nels were sampled sequentially. This is equivalent to applying the linear filter:

$$L = \cos n\omega\tau + j\sin n\omega\tau \quad (5.1)$$

where  $n = 0, 1, 2, 3$  is the order of sampling, and  $\tau$  is the time delay between samples. When appropriate, the inverse of this filter was applied. Finally, the tilt and heading were transformed back into the time domain.

At this point, the slopes are relative to the buoy, and must be transformed into a geographic coordinate system. Let  $r$  be the rotation about the outer gimbal axis,  $p$  the rotation about the inner gimbal axis, and  $^\circ T$  the angle measured clockwise from North to the inner gimbal axis in the coordinate system shown in figure 1a. The coordinate transformation is

$$\begin{aligned} \zeta_2 &= (-\sin^\circ T / \cos p) \tan r + \cos^\circ T \tan p \\ \zeta_3 &= (-\cos^\circ T / \cos p) \tan r - \sin^\circ T \tan p \end{aligned} \quad (5.2)$$

These equations follow from Saenger's (1969) equations (9.6) for  $\psi = 270^\circ$  and  $\psi = 0^\circ$ , and noting  $m = -^\circ T + 90^\circ$ .

The slope series are transformed back into the frequency domain and the appropriate Co- and Quadrature-spectra are computed from the Fourier coefficients of the data using:

$$\begin{aligned} 2C_{ij} &= a_i a_j - b_i b_j \\ 2Q_{ij} &= a_i b_j + a_j b_i \end{aligned} \quad (5.3)$$

where  $a_i, b_i$  are the cosine and sine transformation of the first series,  $a_j, b_j$  are those of the second series. Note that the sign of  $Q_{ij}$  is arbitrary. Our definition agrees with (2.9), but is in disagreement with the convention used by some workers.

The spectral quantities (2.9) are used to calculate various parameters of the ocean-wave directional spectrum. The mean wave direction (at each frequency) is:

$$\tan \beta_0 = N_{01}/N_{10} \quad (5.4)$$

The root-mean-square beamwidth can be calculated several ways; we use

$$\tan 2\gamma = \left( \frac{1 - R}{1 + R} \right)^{1/2} \quad (5.5)$$

where

$$R^2 = [(N_{20} - N_{02})^2 + 4N_{11}^2]/N_{00} \quad (5.6)$$

This agrees with equation (22) in Longuet-Higgins, Cartwright and Smith (1963).

## 6. BUOY RESPONSE TO WAVES

We have estimated the response of the buoy to waves by observing the internal consistency of data recorded at sea and by calibration in a wave tank. In general, the buoy responds as a damped harmonic oscillator with a 1/2 power point near

0.7 Hz. The accuracy of the data meets the design criteria specified in section 3.

Before describing the calibration of the buoy, we first give a gross overview of some typical data. They were obtained off Monterey, California in a 10 m/sec wind when the significant wave height ( $4\langle\zeta^2\rangle^{1/2}$ ) was 2.5 m. A short section of the digitized data from the four transducers (figure 7) indicate the general range of these variables. The root-mean-square acceleration was 10.3% g, and the slope was 6.8°. This is in very good agreement with the values of 10.7% g and 6.1° predicted by eqs. (3.4) and (3.5) using  $\Omega = 0.7$  and  $v = 10$  m/sec.

The first time the buoy was operated at sea we sampled the transducers at the maximum possible rate to determine the optimum rate for later operations. The Nyquist frequency (maximum frequency of the digital spectrum) was 6.25 Hz. The acceleration spectrum recorded on this occasion is shown in figure 8. The noise at low frequencies has a spectral power of around  $10 \text{ cm}^2 \text{ sec}^{-4} \text{ Hz}^{-1}$ . The high-frequency noise is considerably lower, and the Nyquist frequency could be reduced considerably. Consequently, all later data were recorded with a Nyquist frequency at 1.5625 Hz (each signal was sampled 3.125 times per second).

The spectra derived from the Monterey data are plotted in figure 9. The Nyquist frequency is 1.5625 Hz, the resolution is 0.0015 Hz. The figure gives a good indication of the signal/noise ratio of the data. The acceleration values are approxi-

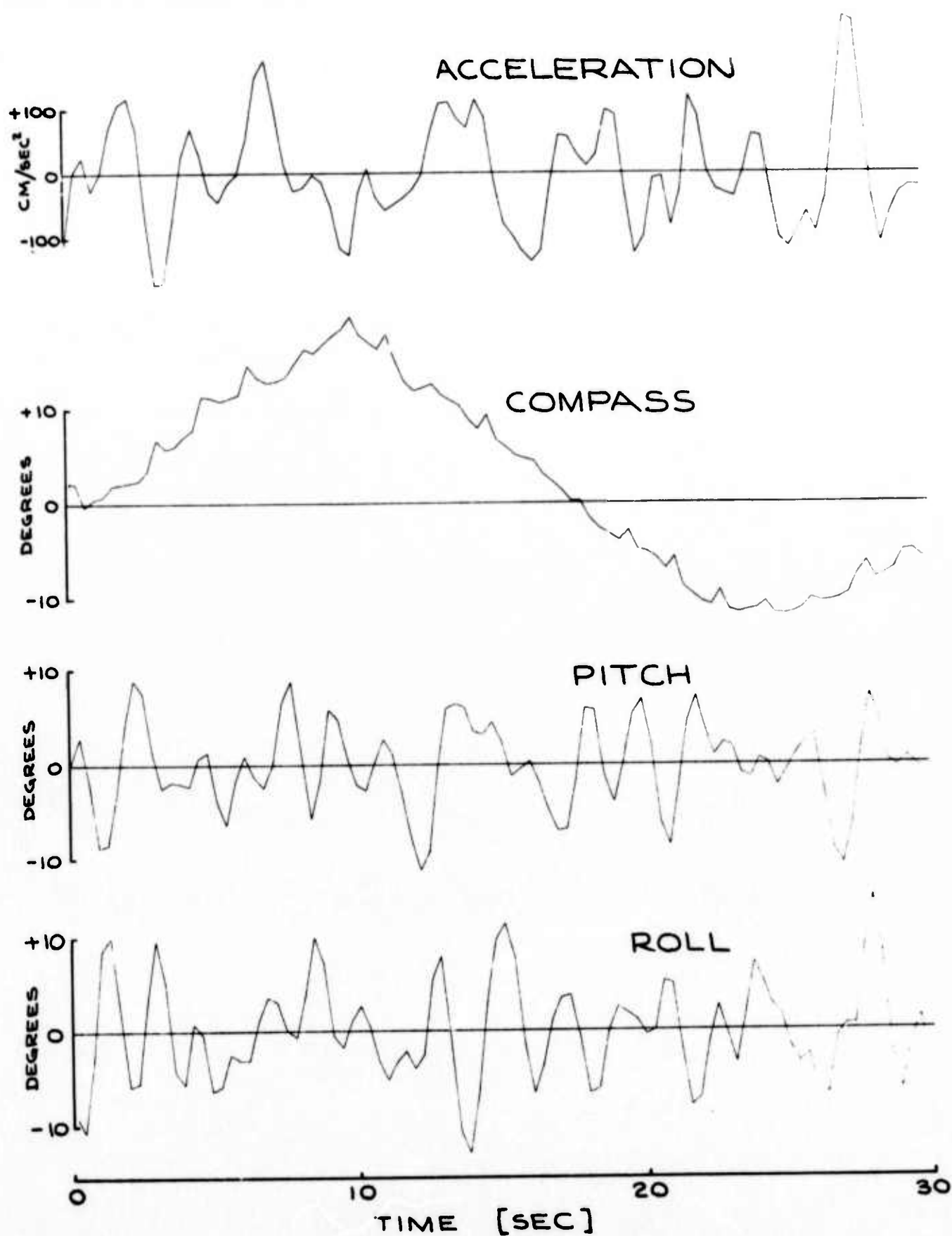


Figure 7. Typical time history of analog signals.

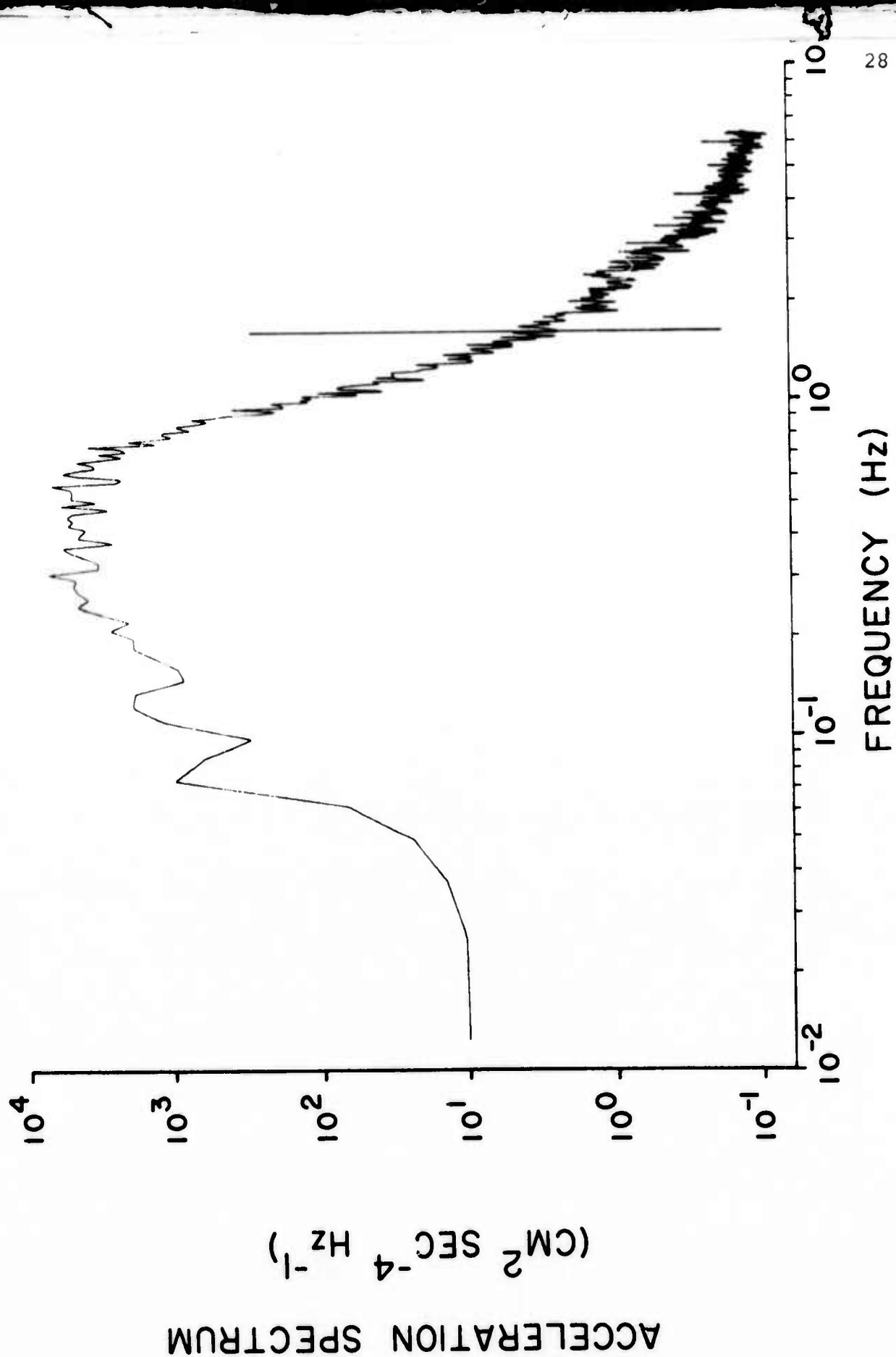


Figure 8. Acceleration spectrum with 6.25 Hz Nyquist frequency. Vertical line is at 1.5625, the Nyquist frequency used for subsequent recordings.

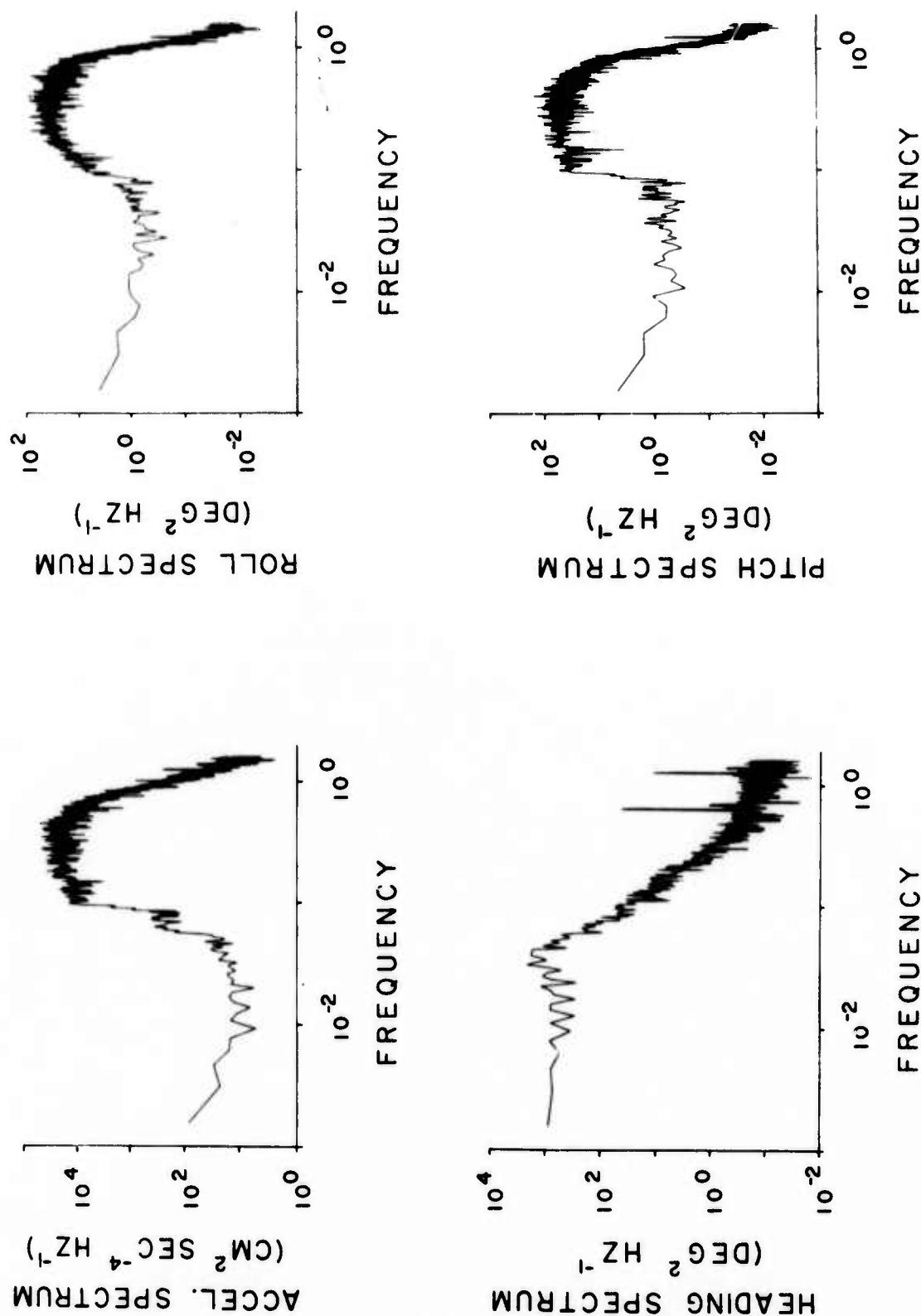


Figure 9. Typical spectra of acceleration, pitch, roll, and compass heading, as a function of frequency in Hz. Nyquist frequency is at 1.5625 Hz. Each spectrum has two degrees of freedom.

mately 1000 times the low-frequency noise, and the low and high frequency ends of the spectrum are identical to those in figure 8. The slope spectra are approximately 100 times larger than the low-frequency noise. The slight rise in energy near zero frequency is due to drift in the sample-and-hold modules, and is the reason for not using them on subsequent days. The buoy heading swings slowly with time, so its spectrum is large at low frequencies. The small spikes in the spectrum are due to aliased 400 Hz noise.

The acceleration noise values require some comment. The noise is 30 times that expected from least count noise (which itself is about equal to the noise from the transducer). It is also about 30 times larger than the noise measured with the instrument on land (no motion). It is probably due to the slightly non-linear way the buoy responds to the motion of the sea, and is not significant for our work. For example, a sinusoidal wave with an amplitude of 0.8 cm at the lowest frequency of interest (0.06 Hz) is detectable with a signal/noise ratio of one. The contribution to this same frequency band by a fully developed sea is 100 times larger.

The buoy was calibrated by observing its response to sinusoidal waves in a tank 2.6 meters wide, 2 meters deep, and 30 meters long. This facility is just barely adequate; fortunately, the best data was obtained near the buoy cut-off frequency. Lower frequency waves were too long for the shallow tank, and shorter waves were not two dimensional. The observed response is plotted in figure 10, together with the

response of a 1/8 ellipsoidal hull calculated by Kim (1966). Although this hull is not very similar to the buoy in plan view, it has nearly the same cross-section along one axis, and it is of shallow draft. The wavenumber  $k$  of the incident waves was calculated from the wave frequency  $\omega$  using  $\omega^2 = gk \tanh kh$ , where  $h$  is the depth of the water. The figure indicates the model accurately predicts the 1/2 power point in the buoy's response, and the ratio of pitch to heave response at low frequencies. This ratio diverges from the observed values at high frequencies.

We estimate the internal consistency of the data by observing how well eqs. (2.10) and (2.11) are met. In general,  $C_{12}$ ,  $C_{13}$ , and  $Q_{23}$  are zero within the statistical fluctuations of the data. Six hours of data recorded in a trade-wind sea, when averaged to give spectral estimates with over 2000 degrees of freedom, yields values for these quantities that are less than 5% of the leading terms ( $C_{11}$ ). To evaluate (2.11) we have averaged together 17.23 hours of data and plotted it in figure 11. The peak near 0.9 Hz is predicted by Kim (cf. figure 10), but the slight rise above unity (near 0.5 Hz) is unexplained. Perhaps it is due to the additional moment of inertia of the high instrument can.

## 7. CONCLUSION

The wave buoy has worked well. Typically we work near shore. The buoy is taken 20-30 km offshore, data is collected

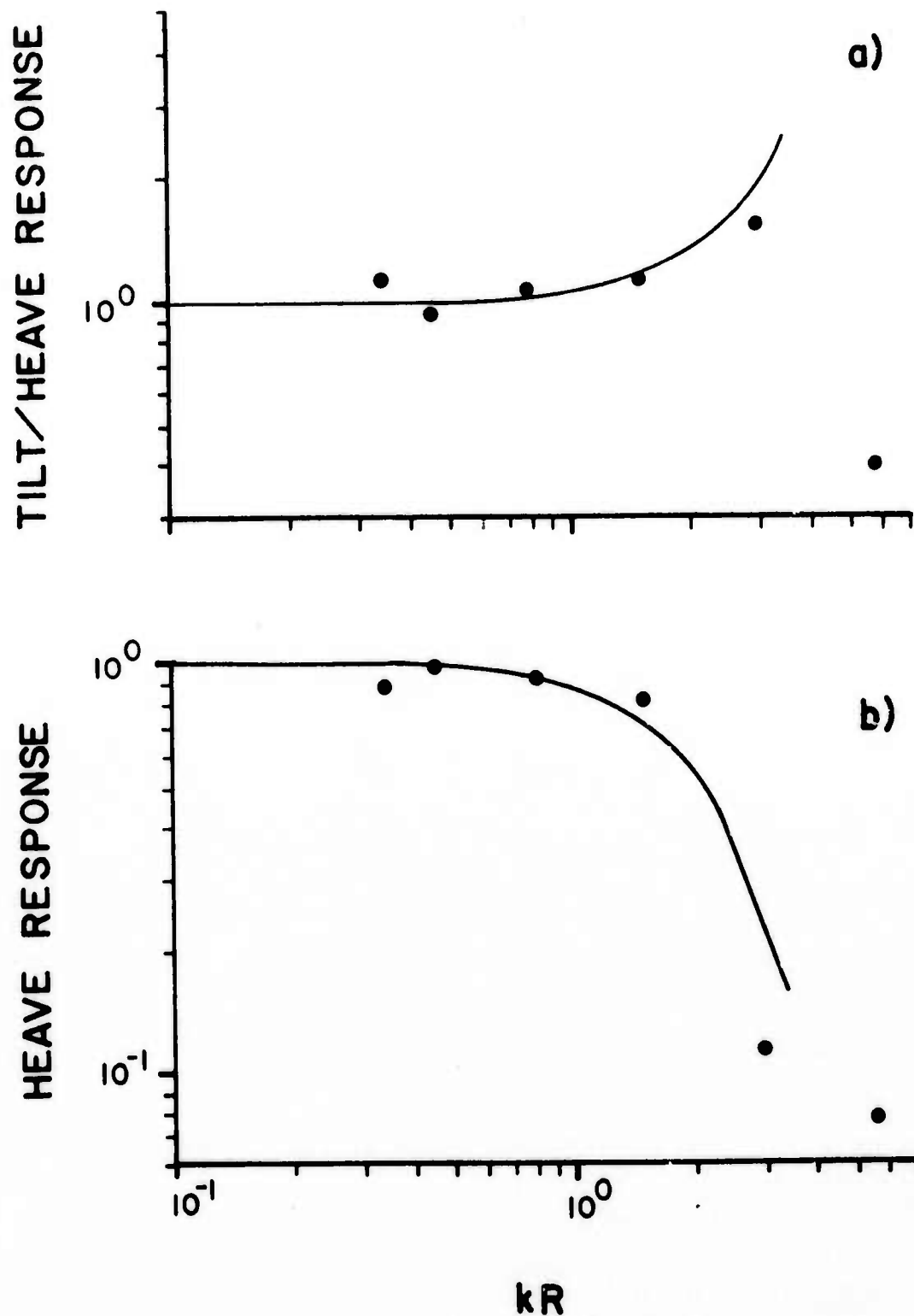


Figure 10. Measured response of buoy to wave tunnel waves (solid points) compared with Kim's (1966) theory (solid line);  $k$  is the wavenumber of the waves,  $R$  is the buoy radius. a) measured slope/( $k \cdot$  measured amplitude). b) measured amplitude/amplitude of waves.

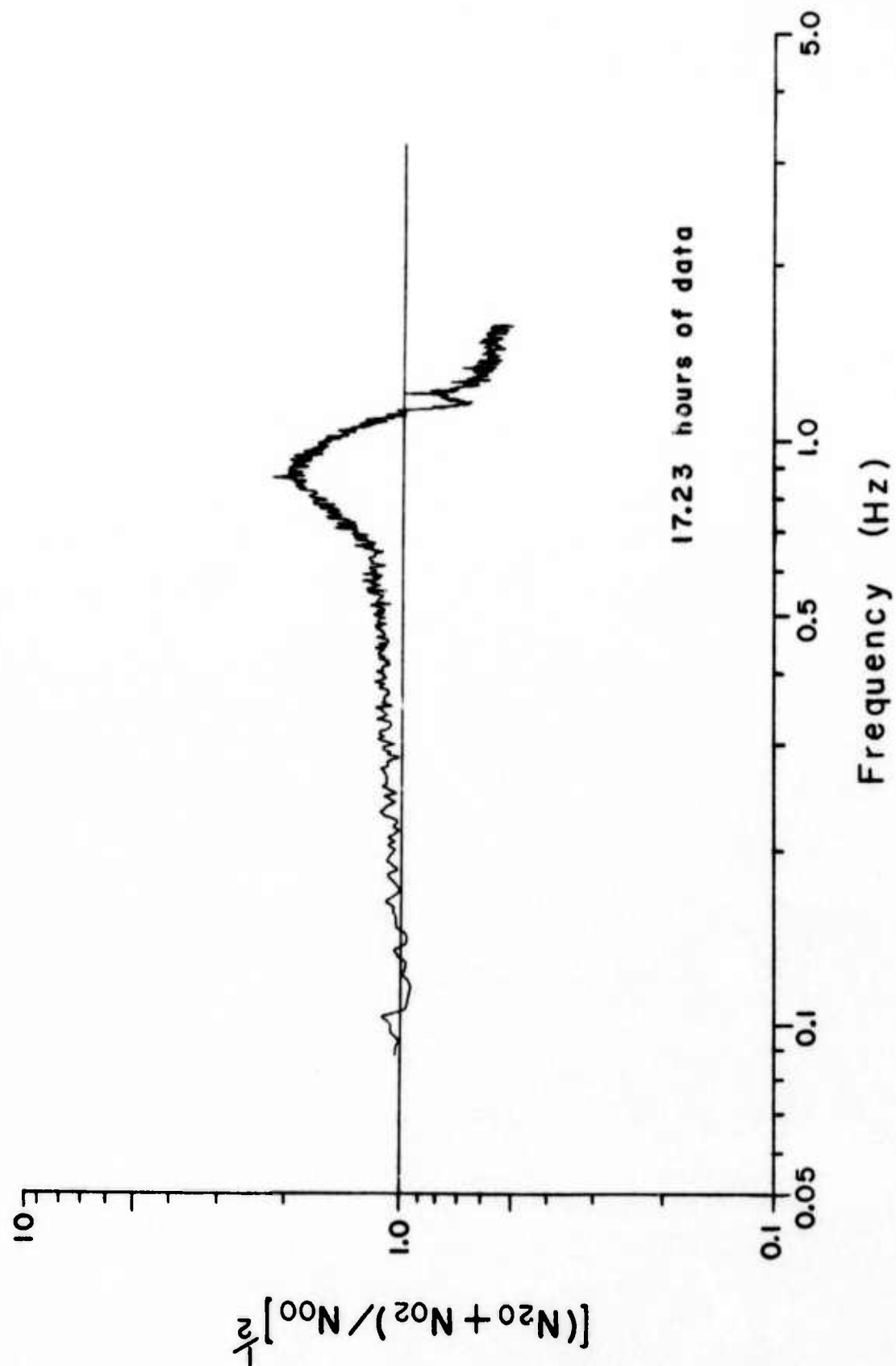


Figure 11. Ratio of wave slope to wave amplitude (times  $k$ ) calculated from 17.23 hours of data recorded at sea.

for three hours, and we return, all in one day. In one year, it has operated at sea on nine different days in four different parts of the world and recorded more than 30 hrs of data. During this time there was only one major failure. On the last day of operation the unit stopped because of low battery voltage. Inspection revealed sea water had corroded away most of the terminals and discharged the batteries.

The data recorder has also worked well. We usually record data in 10 minute segments (records) of 2048 scans. Out of over 200 records recorded, 5% (11 records) have errors. All but two are due to the tape recorder adding an extra 6 bit character in the middle of a record. This is not serious because the data can be recovered with a little extra computer work. We prefer to ignore these records. Once the clock failed to act properly. No data was lost but the time word was incorrect. Once the record was too long. We suspect these errors were due to noise introduced into the logic circuits by strong radar signals from ships used to deploy the buoy. Certainly, the errors were less frequent when the ship did not have a radar or was not close to the buoy.

The buoy has withstood rough handling. It has been shipped from San Diego to Monterey and back, to San Clemente Island and back, to Hawaii and Wake Island. The waterproof connectors have been damaged by inexperienced crane operators on the ships, and the radio antennas have been bent. These items are easily

repaired. The internal components, which are harder to repair, have not been damaged.

The buoy has been deployed by helicopter and from a variety of very small ships with little difficulty. Two men holding lines attached to the bridle mounting points can steady its motion on a rolling ship. It can be lifted by small hydraulic hoists or cranes found on many small workboats, and an inexpensive two-man helicopter can carry it to sea.

Our experience with the buoy shows ways it can be improved. The instrument can could be considerably smaller. It was originally designed to hold the compass, but iron in the inverter caused interference. If only three hours of data are recorded at one time, the much cheaper, low-power, cassette type data recorders could be used. This would make changing tapes easier, and would further reduce the size of the instrument can. Thus the buoy would be more disc shaped, and should have a better response to waves.

In conclusion, we can say the buoy has met the design criteria specified before it was built, and has provided the ocean wave spectra we need in our research program.

## REFERENCES

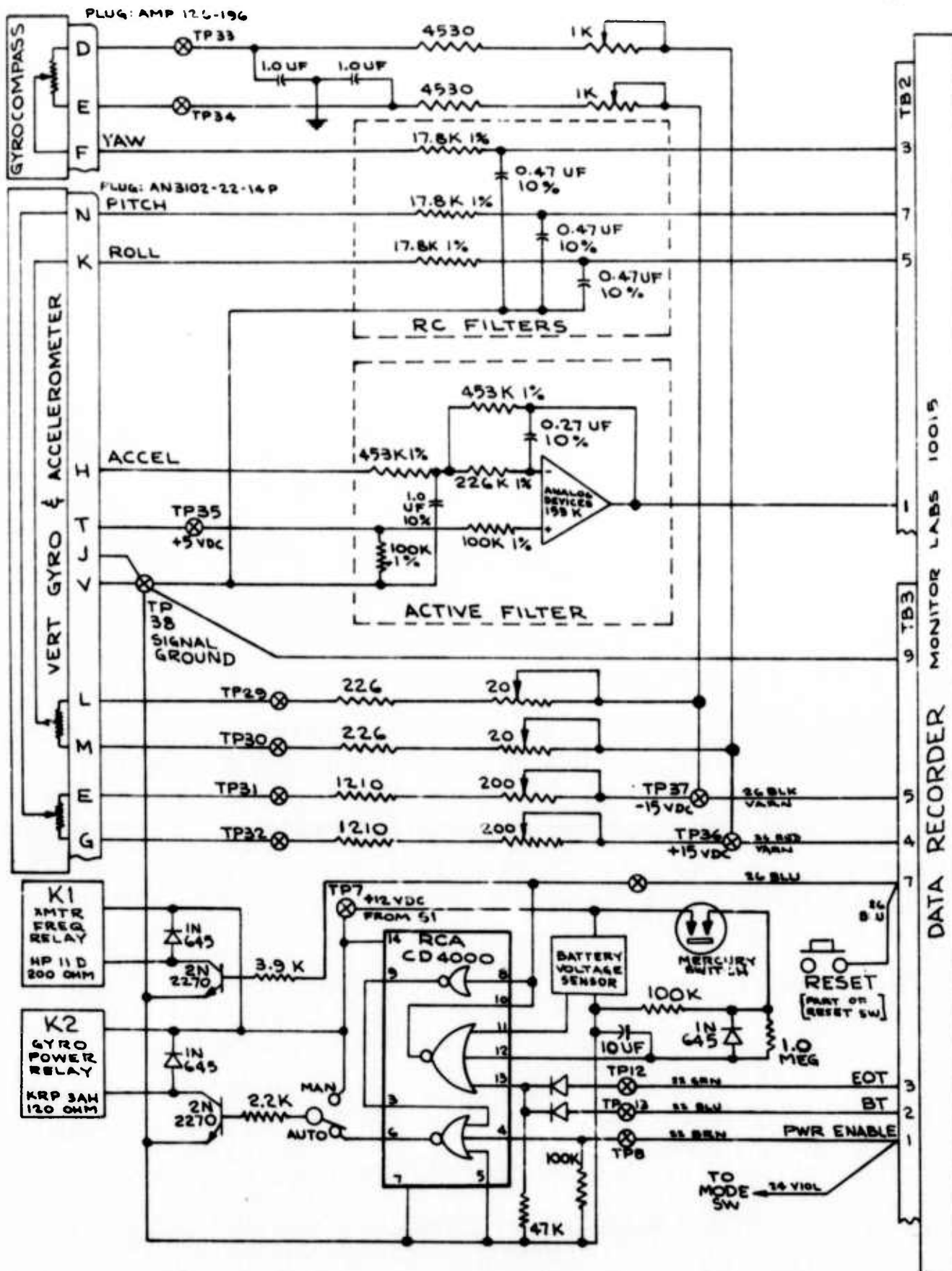
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57

Saenger, R. A. 1969b Measurements of the statistical properties of the ocean surface with instrumented surface floats. Part 2: Engineering and data processing. New York University School of Engineering and Science Technical Report TR-69-10. University Heights, New York.

## APPENDIX

This section contains many of the details necessary to operate the buoy and to analyse the data from it. We have included detailed circuit schematics (figs. A1, A2, A3), program listings, and a list of major components and their source of supply.



● SIGNAL WIRING DIAGRAM ●  
WAVE BUOY

Figure A1.

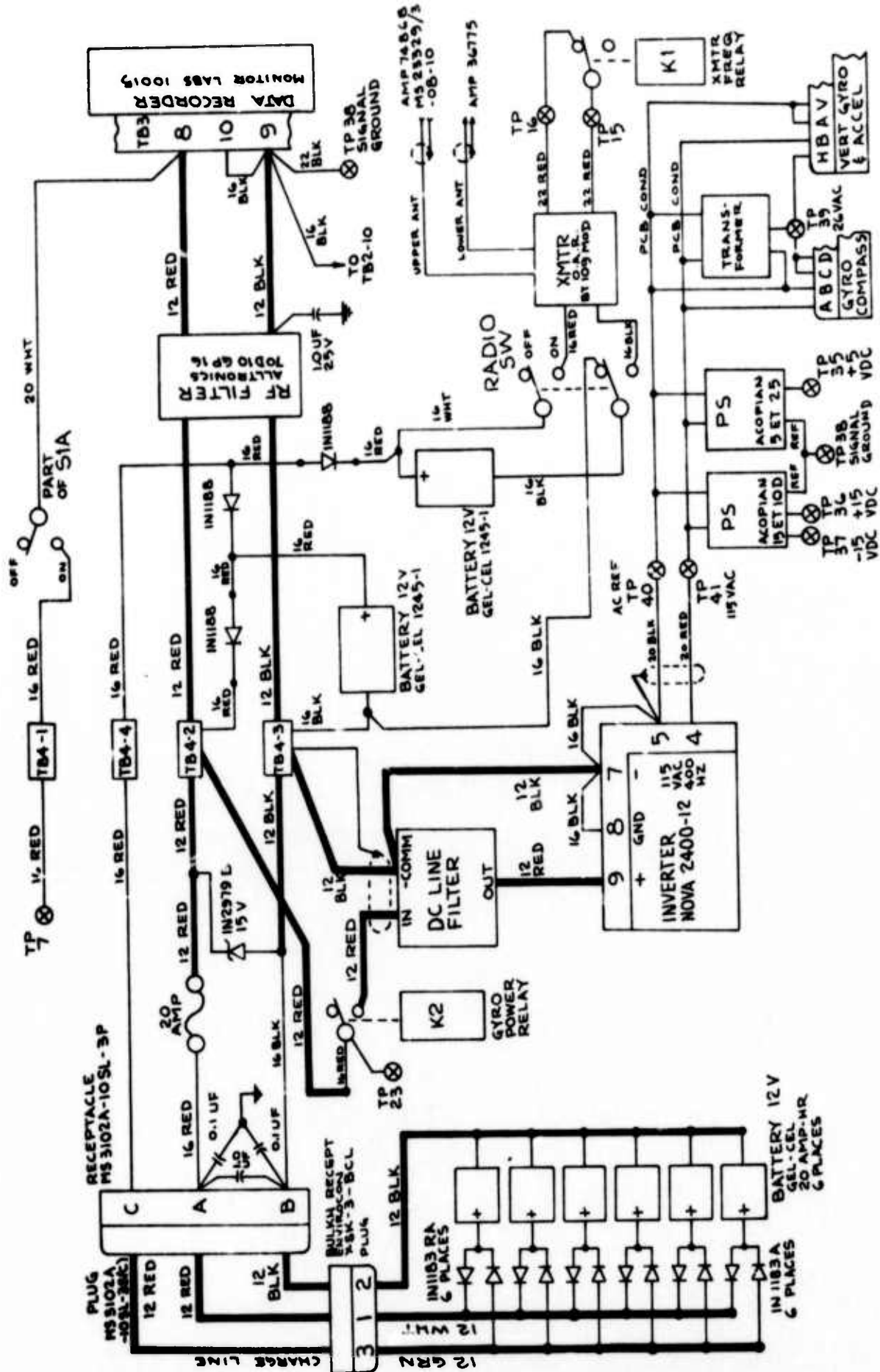
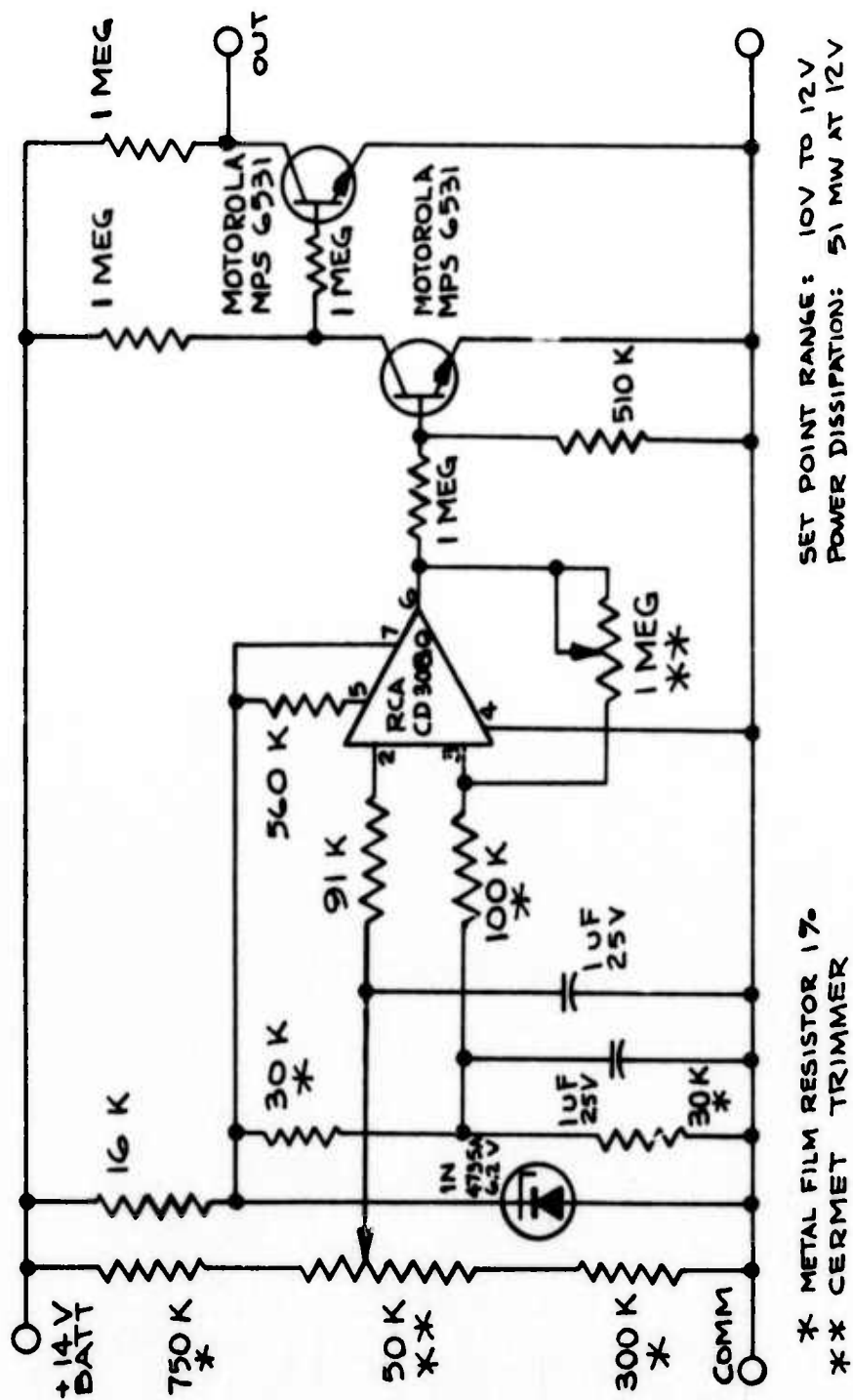


Figure A2.

● POWER WIRING DIAGRAM ●  
WAVE BUOY



## ● BATTERY VOLTAGE SENSOR ●

Figure A3.

### Listing of Computer Program used to Reduce Buoy Data

i L C 1 P

000:0000:0  
BLOCK 15 SEGMENT 00002

PROGRAM WAVEBODY PROVIDES A MEANS OF COMPUTING ESTIMATES OF THE DIRECTIONAL SPECTRUM OF OCEAN WAVES FROM DATA TAPES GENERATED BY THE U. S. SURFACE-FOLLOWING WAVEBODY.

THE CARD INPUT PARAMETERS TO BE SUPPLIED ARE: CARD 1, THE TAPE REEL NAME (6 CHARACTERS); CARD 2, THE TIME-SERIES LENGTH,  $2^{**}NEX$ , FOLLOWED BY THE NYQUIST FREQUENCY IN HERTZ. CARD 3 CONTAINS FIVE INTEGER CONSTANTS VIZ., THE FILE NO. OF THE DATA, THE FIRST RECORD OF THE DATA TO BE USED, THE NUMBER OF RECORDS TO BE AVERAGED, AN INTEGER VARIABLE, "CHANNELS", WHICH SELECTS WHICH OF THE FOUR DATA CHANNELS ARE TO BE USED. IF ALL CHANNELS ARE REQUIRED, AS IN COMPUTING DIRECTIONAL SPECTRA, THEN SET CHANNELS=1111 (BINARY) = 15 (DECIMAL). FOR INSTANCE, IF ONLY CHANNEL 1 POWER SPECTRUM (VERT. ACCELERATION CONVERTED TO SURFACE ELEVATION) THEN SET=1000 (BINARY) = 8 (DECIMAL INPUT VALUE). "AVEFQ" IS THE NUMBER OF FREQ. BANDS AVERAGED OVER AFTER THE AVERAGING OVER SPECTRA FROM INDIVIDUAL RECORDS HAS BEEN DONE. THE NEXT CARD READ INPUTS: A BOOLEAN VARIABLE "LAV" WHICH, IF SET TRUE, DOES A LOGRITHMIC TYPE AVERAGING OVER SPECTRAL BANDS (CAUTION: IF LAV=TRUE, SET AVEFQ=1), A BOOLEAN VARIABLE "SAHIN", WHICH IF SET TRUE MEANS THAT THE SAMPLE AND HOLD MODULES OF THE WAVEBUOY WERE OPERATIONAL AT THE TIME OF DATA COLLECTION; THE MAGNETIC COMPASS DEVIATION FROM TRUE NORTH AND EITHER "F" OR "a" CHARACTER FOLLOWING; "FLIM" IS THE GREATEST WAVE PERIOD TO BE INCLUDED IN FINDING THE VARIANCE; IF BLANK THIS IS AUTOMATICALLY SET TO  $2^{**}(NEX-1)/NYQUIST$ , THE LONGEST PERIOD FOR THE TIME SERIES LENGTH. FINALLY, THERE IS A CARD WHICH CONTAINS SIX BOOLEAN VARIABLES SPECIFYING WHICH TABLES ARE TO BE PRINTED OUT AND WHICH TYPE(S) OF SPECTRA ARE TO BE PUNCHED.

THIS PROGRAM UTILIZES THE "SSET INSTALLATION" CONTROLL CARD  
IN ORDER TO ACCESS THE SYSTEM INTRINSICS: FFT, BITRV2, FITR, SINCS.

JOE JOY , PAUL HANSEN  
BOB STEWART  
APRIL, 1973.

000:0000:0

BLOCK 13 SEGMENT 00002

002:0000:0

092:0070:0

002:0000:0

002:0000:0

၈၈၂:၅၈၇၈:။

002:0000:01

ה:הר:ח:ח:ח

002:0000:0

002:0000:0  
001:0000:0

002:0000:0

002:0000:0  
102:0000:0

002:0010:0  
002:0000:0

002:0010:1

002,0000-0

022-0010:2

002:0010:2

002:0010:0

002:0022:1

002:06.00:0

002:0007:7

002:0000:0

၇၇၂:၈၈၈:၇

002:0000:0

002:0070:

002:006.0:

002:0000:

002:0000:0

002: 0000: 0

002:0000:0

002:0000:0

002:0000:0

002:0000:0  
002:0000:0

002:0000:1

002:0030:0

002:0000:0

002:0020:1

002:0000:

005:0030:4





1

```

J := 0;
CASE L-1 OF BEGIN
  GETFIELD(J,23);
  GETFIELD(J,11);
  GETFIELD(J+1, 47);
  GETFIELD(J+1, 35);
END OF CASES;
REPLACE POINTER(1[L,0]) BY 4"000000000000" FOR NWORDS WORDS;
ERRCT := 0;
MEAN[L] := R[L,0];
IF L EQL 2 THEN LIMIT:=256 ELSE LIMIT:=1024;
LIMIT=256 CORRESPONDS TO 22.5 DEG. AZIMUTH
LIMIT=1024 CORRESPONDS TO 22 DEG. TILT OR .5*G ACCEL.

J := 1;
DO BEGIN
  COMMENT ERROR IN DATA FIRST OCTAL DIGIT DIFFERENCE;
  IF ABS(R[L,J] - R[L,J-1]) GTR LIMIT THEN
    IF ERRCT := *+1 GTR 4 THEN BEGIN
      *WRITE(PRINTER,"ERROR IN READTAPE: TOO MANY BAD DATA POINTS.",
        " LAST ONE AT ", 14, ".", ">", J);
      GO ERROR;
    END ELSE BEGIN
      *WRITE(PRINTER,"ERROR IN READTAPE: BAD DATA POINT AT: ROW (" ,
        11, " ), COLUMN(" , 14, " ). IN REFERENCE TO " , F7.2, " , POINT " ,
        F7.2, " OUT OF LINE">, L,J,R[L,J-1], R[L,J]);
      R[L,J] := R[L, J-1];
    END;
    MEAN[L] := MEAN[L] + R[L,J];
  END UNTIL J := * + 1 GEQ NWORDS;
  XMEAN := MEAN[L] / NWORDS;
  CF := CAL[L];
  MEAN[L] := (XMEAN - 2048) * CF;
  IF L EQL 1 THEN
    *WRITE(PRINTER,"MEAN VALUE OF CHANNEL ",11," IS ",F11.5,
      " CM./SEC.**2">,L,MEAN[L]) ELSE
    *WRITE(PRINTER,"MEAN VALUE OF CHANNEL ",11," IS ",F11.5,
      " RADIANS.">,L,MEAN[L]);
  IF L EQL 4 THEN *WRITE(PRINTER,</>);
  J := 0;
  DO R[L,J] := (R[L,J]-XMEAN) * CF UNTIL J:= * + 1 GEQ NWORDS;
END;
GO LEAVE;
*FOR: ERR := TRUE;
LEAVE:END READTAPE;

```



\* FUNCTIONS A AND B ARE REAL AND IMAGINARY PARTS OF INVERSE FILTER RESP.  
IF J EQL 1 THEN BEGIN

W02:=(W0:=W\*K\*W11)\*\*2 - 1.;  
IF SRMIN THEN BEGIN A:=W02; B:=S12\*W0; END  
ELSE BEGIN  
A:=W02\*CS - S12\*W0\*SN;  
B:=W02\*SN + S12\*W0\*CS; END;  
IF N EQL NPPTS THEN B:=0.;  
R[J,N]:=A\*TEMPR + B\*TEMPI;  
I[J,N]:=A\*TEMPI - B\*TEMPR;

END ELSE BEGIN

W0:=W\*K\*W12;  
IF SRMIN THEN BEGIN A:=1.; B:=W0; END ELSE BEGIN  
A:=CS + W0\*SN; B:=W0\*CS - SN; END;  
IF N EQL NPPTS THEN B:=0.;  
R[J,N]:=A\*TEMPR - B\*TEMPI;  
I[J,N]:=A\*TEMPI + B\*TEMPR;  
N:=N+1;

END;

END;

;

N:=1; \* CONVERT ACCELERATION TRANSFORM TO SURFACE ELEVATION.

IF J EQL 1 THEN BEGIN

THRU (NPPTS-1) DO BEGIN

IF N EQL NPPTS THEN

W0:=-1./((N\*W)\*\*2) ELSE W0:=-1./((NPPTS-N)\*W)\*\*2;  
R[1,N]:=W0\*R[1,N]; I[1,N]:=W0\*I[1,N];  
N:=N+1;

END;

END ELSE BEGIN

BEIRVZ(R[J,\*],I[J,\*],MEX);

FFTR(R[J,\*],I[J,\*],S1,CO,MEX);

N:=0; DO R[J,N]:=R[J,N]/NPPTS UNTIL N:=N+1 GEO NPPTS;

REPLACE POINTER(I[J,\*]) BY 0. FOR NPPTS WORDS;

END;

END;

END ADJPHASE;

\*\*\*\*\*

000:0070:5  
000:0070:5

000:0072:0

000:0070:1

000:0079:4

000:007A:1

000:007D:0

000:007F:5

000:0081:5

000:0085:3

000:0089:1

000:0089:1

000:0089:1

000:008B:3

000:008F:5

000:0093:3

000:0095:3

000:0099:1

000:009C:5

000:009E:1

000:009F:2

000:009F:2

000:00A0:0

000:00A1:1

000:00A5:4

000:00A6:3

000:00AE:0

000:00B3:2

000:00B4:4

000:00B5:5

000:00B6:2

000:00B6:2

000:00BF:0

000:00B8:0

000:00C5:4

000:00C6:1

000:00C8:1

000:00CA:3

ADJPHASE(000) IS 0004 LONG

000:0030:4

```

* -----
LAST:= 4"CS";
REST:= 4"ES";
TAPEBUF[*].IUCW := 0 & 1[44:1] & 6[33:3] & 1[30:1]; & 7-TRK, 200 RPI
TAPEBUF[*].IOPASK := 0 & 1[7:1]; & SUPPRESS PARITY ERROR RETRY.
FSTEP := XNYQUIST * 2./NWORDS;
OMEG := 1./(2. * PI * FSTEP);
SINCOS(SI, CO, MEX); & SET UP SIN-COS TABLE FOR FFTF
J := 1;
LC BEGIN
  FREQ[J] := FSTEP * J;
  PER[J] := 1./FREQ[J];
  OMEG4[J] := (OMEG/J) ** 4;
  K140[J] := (KONE[J] := .0402840996*(FSTEP*J)**2)**2;
  JACOB[J] := 480200./12.*PI*FSTEP*J**3;
END UNTIL J := * + 1 GEQ N;
  PS[0] := OMEG4[0] := FREQ[0] := PER[0] := 0.;
  VV := 0;
  READ(CARD,<2(I5,X5),F6.1,X1,A1,X5,F6.1>,IAV,SAHIN,MAGDEV,EORW,TLIM);
  READ(CARD,<6(L5,X5)>, TABLE1, TABLE2, TABLE3, PUNCHXS, PUNCHPS, PUNCHDS);
  IF TLIM LEQ 0. THEN TLIM:=NM1/XNYQUIST;
  IF LAV THEN WRITE(PRINTER,<"SPECTRAL BANDS AVERAGED ON LOGRITHMIC ",
    "BASIS.">) ELSE BEGIN
    FREEDOM:=2*NREC*AVEFQ;
    WRITE(PRINTER,<I2," ADJACENT FREQS. AVERAGED YIELDING ",I3,
      " DEGREES OF FREEDOM IN SPECTRAL ESTIMATES.">,
      AVEFQ,FREEDOM); END;
  IF MEX LEQ 3 AND LAV THEN BEGIN
    WRITE(PRINTER,<"TIME HISTORY TOO SHORT TO IMPLIMENT LOGRITHMIC"
      " AVERAGING.">); GO TO FINI; END;
  WRITE(PRINTER,<"SAMPLE & HOLD MODULES IN=",L5>,SAHIN);
  WRITE(PRINTER,<"MAGNETIC COMPASS DEVIATION=",F6.1,X1,A1,"."/;>,
    MAGDEV,EORW);
  MAGDEV:= MAGDEV*PI/180.;
  WRITE(PRINTER,<6(L5,X5)>,TABLE1, TABLE2, TABLE3, PUNCHXS, PUNCHPS, PUNCHDS);
  TAPESTAR1(BOUYTAPL, TAPEBUF, NWORDS+1, NFILE, FIRSTREC, ERR);
  REC:=1;
  NEXT: BEGIN READTAPE(NFILE, REC+FIRSTREC-1, CHANNELS);
    IF NOT ERR THEN ADJPHASE(R,I,SI,CO,MEX,CHANNELS,XNYQUIST,SAHIN)
      ELSE GO TO AGAIN;
    NN:= NN + 1;
    K:=0;
    IF EORW EQL EAST THEN DO R[2,<]:=* + MEAN[2] + MAGDEV
      UNTIL K:=*+1 GEQ NWORDS ELSE
    IF EORW EQL WEST THEN DO R[2,<]:=* + MEAN[2] - MAGDEV
      UNTIL K:=*+1 GEQ NWORDS ELSE GO TO EXIT;
    K:=0;
    CONVERT ANGLE TIME HISTORIES TO SLOPE TIME HISTORIES CHANS. 3,4.
    THRU NWORDS DO BEGIN
      SINAZ:=SIN(R[2,K]); COSAZ:=COS(R[2,K]);
      TANROLL:=TAN(R[3,K]); TANPITCH:=TAN(R[4,K]);
      COSPITCH:=COS(R[4,K]);
      R[3,K]:= -COSAZ*TANROLL/COSPITCH - SINAZ*TANPITCH;
      R[4,K]:= +SINAZ*TANROLL/COSPITCH - COSAZ*TANPITCH;

```

3

3

3

3

3

3

3

4

```

005:0130:4
005:0030:4
005:0031:3
005:0032:2
005:0035:1
005:0037:0
005:003A:1
005:003F:1
005:0041:1
005:0041:5
005:0041:5
005:0043:4
005:0046:3
005:0049:0
005:004E:0
005:0054:0
005:0056:2
005:0059:5
005:005A:3
005:0070:5
005:0069:2
005:0038:5
005:008E:3
005:0132:4
005:0134:4
005:0096:3
005:0097:2
005:0144:4
005:00A6:3
005:00A8:2
005:00A8:3
005:00BA:4
005:00BD:2
005:013A:1
005:00CF:4
005:01E7:1
005:00E7:4
005:00EB:4
005:01EB:1
005:00EC:2
005:00EF:2
005:00F4:1
005:00F4:5
005:00F6:1
005:00F6:1
005:00F6:5
005:00FA:2
005:00FD:2
005:0101:2
005:0114:2
005:0105:0
005:0115:0
005:0109:1
005:010D:1
005:0111:3
005:0113:4
005:0117:4

```

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```

IF EORN EQL EAST THEN R[2,K]:=* - MEAN[2] - MAGDEV ELSE
R[2,K]:=* - MEAN[2] + MAGDEV;
K:=*+1;
END;

FOR NCHANNEL:=1 STEP 1 UNTIL 4 DO IF CHANNELS.[4-NCHANNEL:1] NEQ 0
THEN BEGIN IF NCHANNEL GEQ 2 THEN BEGIN
  FFT(R[NCHANNEL,*], I[NCHANNEL,*], SI, CO, MEX);
  BITRV2(A[NCHANNEL,*], I[NCHANNEL,*], MEX);
  END;

  CALCULATE POWER SPECTRA; CALCULATE VARIANCES.
  VARN:=0.; K:=0;
  DO BEGIN
    X := (R[NCHANNEL, K] ** 2 + I[NCHANNEL, K] ** 2)*SCALE;
    IF NCHANNEL EQL 1 AND K LSS INTEGER(1./(TIM*FSTEP)) THEN
      X:=0.;
    A[NCHANNEL,K]:=R[NCHANNEL,K]; B[NCHANNEL,K]:=I[NCHANNEL,K];
    VARN := * + X;
    PSA[NCHANNEL, K] := IF NN EQL 1 THEN X ELSE
    PSA[NCHANNEL,K] + X; END UNTIL K:=*+1 GEQ N;

  CASE NCHANNEL-1 OF BEGIN
    WRITE(PRINTER,<,"SURFACE ELEVATION VARIANCE=",E12.5," CM**2">,VARN);
    WRITE(PRINTER,< "HEADING VARIANCE=",E12.5," RADIANS**2">,VARN);
    WRITE(PRINTER,< "N-S SLOPE VARIANCE=",E12.5," SLOPE**2 (NO UNITS)">,
      VARN);
    WRITE(PRINTER,< "E-W SLOPE VARIANCE=",E12.5," SLOPE**2 (NO UNITS)",
      ////>,VARN);
  END OF CASES;

  ENL; * END OF FFT LOOP. ....

  CALCULATE CROSS SPECTRA
  K:=1; DO CSN[K]:=*(A[1,K]*A[3,K] + B[3,K]*B[1,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO QSN[K]:=*(A[3,K]*B[1,K] - A[1,K]*B[3,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO CS4[K]:=*(A[1,K]*A[4,K] + B[4,K]*B[1,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO QSN[K]:=*(A[4,K]*B[1,K] - A[1,K]*B[4,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO CNA[K]:=*(A[3,K]*A[4,K] + B[4,K]*B[3,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO QNA[K]:=*(A[4,K]*B[3,K] - A[3,K]*B[4,K])*SCALE
  UNTIL K:=*+1 GEQ N - 1;
  K:=1; DO PS[K]:=*(A[1,K]**2 + B[1,K]**2)*SCALE/OMEGA[K]
  UNTIL K:=*+1 GEQ N - 1;

  ENL;

  AGAIN:REC:=*+1;
  IF REC LEJ NREC THEN GO TO NEXT;
  EXIT: IF NN GTR 7 THEN BEGIN
    NCHANNEL:=1; Z:=1./NN;

```

005:0110:3  
 005:0111:4  
 005:0123:0  
 005:0124:2  
 005:0125:3  
 005:0125:3  
 005:0125:3  
 005:0127:5  
 005:012A:0  
 005:012E:2  
 005:0131:4  
 005:0131:4  
 005:0131:4  
 005:0133:0  
 005:0133:0  
 005:0137:3  
 005:0138:0  
 005:013C:1  
 005:0142:3  
 005:0143:5  
 005:0147:3  
 005:014B:5  
 005:014B:5  
 005:014E:3  
 005:015D:1  
 005:016E:4  
 005:016D:3  
 005:017A:1  
 005:017C:0  
 005:018B:4  
 005:013B:0  
 005:018B:0  
 005:013D:2  
 005:016D:2  
 005:018L:2  
 005:0193:2  
 005:0196:5  
 005:019C:5  
 005:01A0:2  
 005:01AB:2  
 005:01A9:5  
 005:01AF:5  
 005:018J:2  
 005:0179:4  
 005:01BD:1  
 005:01C3:3  
 005:01C7:0  
 005:01CC:1  
 005:01CF:4  
 005:01CF:4  
 005:01CF:4  
 005:01CF:4  
 005:01D1:7  
 005:0112:2  
 005:01D2:2  
 005:0113:3

```

DO BEGIN
  K:=1;
  IF BOOLEAN(CHANNELS.[4-NCHANNEL:1]) THEN
    IF NCHANNEL EQL 1 THEN DO BEGIN
      PS[K]:=* * Z;
      PSA[1,K]:=* * Z;      END
      UNTIL K:==+1 GEQ N-1 ELSE
      DO PSA[NCHANNEL,K]:=* * Z
      UNTIL K:==+1 GEQ N-1 ELSE
    END UNTIL NCHANNEL:==+1 GTR 4;
  END ELSE BEGIN WRITE(PRINTER,<"UNSUCCESSFUL TAPE READ">);
    GO TO FINI;      END;

  K:=0;
  IF NN GTR 1 THEN DO BEGIN
    CSN[K]:=* * Z;      QSN[K]:=* * Z;      CSW[K]:=* * Z;
    PSN[K]:=* * Z;      CNW[K]:=* * Z;      QNW[K]:=* * Z;
  END UNTIL K:==+1 GEQ N;
  WRITE(PRINTER[SKIP 1]);
  FOR NCHANNEL:=1,3,4 DO BEGIN
    VARN:=0.;      K:=0;
    DO VARN:=* + PSA[NCHANNEL,K] UNTIL K:==+1 GEQ N;
    IF NCHANNEL EQL 1 THEN
      WRITE(PRINTER,<"AVERAGE VARIANCE OF ",12," RECORDS, CHAN.#",
        11," = ",E12.5," CM.**2",/,>,NREC,NCHANNEL,VARN)
    ELSE
      WRITE(PRINTER,<"AVERAGE VARIANCE OF ",12," RECORDS, CHAN.#",
        11," = ",E12.5," SLOPE**2 (NO UNITS)",/,>,NREC,NCHANNEL,VARN);
    END;

  IF TABLE1 THEN BEGIN
    WRITE(PRINTER,<"/", "UNNORMALIZED POWER SPECTRA AVERAGED OVER ",12,
      " RECORDS.",NREC);
    WRITE(PRINTER,<X55,"ACCEL.",X3,"SURFACE",X4,"COMP.",
      X3,"N-SLOPE",X3,"E-SLOPE",/,>);
    WRITE(PRINTER,<" STEP", X2, "FREQUENCY", X2, "PERIOD", X3, "OMEGA-4",
      X3, "CHANNEL(S):", 5110/,>, FOR NCHANNEL := 1,1,2,3,4 DO
      IF CHANNELS.[4-NCHANNEL:1] EQL 1 THEN NCHANNEL);
    J:=0;
    DO WRITE(PRINTER,<14,3E10.2,X18,5E10.2>, J,FREQ[J],PER[J],OMEGA4[J],
      IF CHANNELS.[3:1] EQL 1 THEN PS[J], FOR NCHANNEL:=1,2,3,4 DO
      IF CHANNELS.[4-NCHANNEL:1] EQL 1 THEN PSN[NCHANNEL,J])
      UNTIL J:==+1 GEQ N;
    END;

  IF CHANNELS LSS 15 THEN GO TO FINI;
  %AVERAGE TOGETHER ADJACENT FREQUENCY BANDS.
  J:=1;
  IF LAV THEN BEGIN
    X:=1./FSTEP;      Y:=-X;
    DO BEGIN AVEPER[J]:=1./FREQ[J]; PS[J]:=* * X; PSA[1,J]:=* * X;
      PSA[2,J]:=* * X; PSA[3,J]:=* * X; PSA[4,J]:=* * X;
      CSN[J]:=* * X; QSN[J]:=* * X; CSW[J]:=* * Y;
      QSW[J]:=* * Y; CNW[J]:=* * Y; QNW[J]:=* * Y;
    END UNTIL J:==+1 GEQ 65;
  END

```

```

005:0107:1
005:0117:0
005:0107:4
005:0119:2
005:0108:0
005:011C:5
005:01FF:0
005:01E1:4
005:01E4:1
005:01E7:3
005:01E9:3
DATA IS 00FC LONG
005:01EF:4
005:01F0:1
005:01F0:1
005:01F0:5
005:01F2:0
005:01F7:1
005:01FL:0
005:01FF:2
005:0214:1
005:020B:2
005:021C:4
005:0211:2
005:0212:0
005:0214:2
005:021F:0
005:0224:4
005:0227:0
005:0237:1
005:023A:3
005:023B:3
005:023B:2
005:023D:1
005:0249:1
005:024B:0
005:024E:4
005:0250:3
005:0262:2
005:026E:1
005:026E:5
005:0280:2
005:028D:5
005:0282:4
005:029C:3
005:029C:3
005:029C:3
005:029D:5
005:029D:5
005:029D:5
005:029E:3
005:029F:2
005:02A3:0
005:02AA:0
005:02B0:5
005:02B6:2
005:02BB:5

```

```

VPLAVEFQ:=1;          ENLPT:=128;          J:=65;
LOOPER:VALAVEFQ:=* * 2;
DO BEGIN
  K:=1;
  DO BEGIN
    FREQ[J]:=* + FREQ[J+K];  OMEGA4[J]:=* + OMEGA4[J+K];
    PS[J]:=* + PS[J+K];
    PSA[1,J]:=* + PSA[1,J+K];  PSA[2,J]:=* + PSA[2,J+K];
    PSA[3,J]:=* + PSA[3,J+K];  PSA[4,J]:=* + PSA[4,J+K];
    CSN[J]:=* + CSN[J+K];  QSN[J]:=* + QSN[J+K];
    CSW[J]:=* + CSW[J+K];  QSW[J]:=* + QSW[J+K];
    CNW[J]:=* + CNW[J+K];  QNW[J]:=* + QNW[J+K];
    JACOB[J]:=* + JACOB[J+K];  KONE[J]:=* + KONE[J+K];
    KTWO[J]:=* + KTWO[J+K];
  END UNTIL K:=*+1 GEQ VALAVEFQ;

  Z:=1./VALAVEFQ;          X:=1./((VALAVEFQ*FSTEP);          Y:=-X;
  BEGIN
    NOTE: (THE "NATURAL" RIGHT-HANDED BODY COORDINATES ARE NORTH & WEST,
    BUT EAST AND NORTH ARE MORE CONVENTIONAL; SO, SINCE E. SLOPE=-X.SLOPE
    FOR NORMALIZATION MULTIPLY ALL CROSS SPECTRA INVOLVING W. SLOPE BY
    Y = -X ON BY 2 IF ONLY AVERAGING IS DONE.
    FREQ[J]:=* * Z;  OMEGA4[J]:=* * Z;  PS[J]:=* * X;
    PSA[1,J]:=* * X;  PSA[2,J]:=* * X;  PSA[3,J]:=* * X;
    PSA[4,J]:=* * X;  CSN[J]:=* * X;  QSN[J]:=* * X;
    CSW[J]:=* * Y;  QSW[J]:=* * Y;  CNW[J]:=* * Y;  QNW[J]:=* * Y;
    JACOB[J]:=* * Z;  KONE[J]:=* * Z;  KTWO[J]:=* * Z;

  END;
  AVEPEN[J]:=1./FREQ[J];
  END UNTIL J:=* + VALAVEFQ GEQ ENLPT;

  ENLPT:=* * 2;
  IF ENLPT LEQ NML THEN GO TO LOOPER;

END ELSE DO BEGIN
  K:=1;
  DO BEGIN
    FREQ[J]:=* + FREQ[J+K];  OMEGA4[J]:=* + OMEGA4[J+K];
    PS[J]:=* + PS[J+K];
    PSA[1,J]:=* + PSA[1,J+K];  PSA[2,J]:=* + PSA[2,J+K];
    PSA[3,J]:=* + PSA[3,J+K];  PSA[4,J]:=* + PSA[4,J+K];
    CSN[J]:=* + CSN[J+K];  QSN[J]:=* + QSN[J+K];
    CSW[J]:=* + CSW[J+K];  QSW[J]:=* + QSW[J+K];
    CNW[J]:=* + CNW[J+K];  QNW[J]:=* + QNW[J+K];
    JACOB[J]:=* + JACOB[J+K];  KONE[J]:=* + KONE[J+K];
    KTWO[J]:=* + KTWO[J+K];
  END UNTIL K:=*+1 GEQ AVEFQ;

  Z:=1./AVEFQ;          X:=1./((AVEFQ*FSTEP);          Y:=-X;
  BEGIN
    FREQ[J]:=* * Z;  OMEGA4[J]:=* * Z;  PS[J]:=* * X;
    PSA[1,J]:=* * X;  PSA[2,J]:=* * X;  PSA[3,J]:=* * X;
    PSA[4,J]:=* * X;  CSN[J]:=* * X;  QSN[J]:=* * X;
    CSW[J]:=* * Y;  QSW[J]:=* * Y;  CNW[J]:=* * Y;  QNW[J]:=* * Y;
    JACOB[J]:=* * Z;  KONE[J]:=* * Z;  KTWO[J]:=* * Z;

  END;

```

```

4      005:02B8:1
      005:02C0:3
      005:02C0:3
      005:02C2:0
      005:02C2:7
      005:02C2:4
      005:02C2:4
      005:02C8:0
      005:02CA:4
      005:02D1:3
      005:02D6:0
      005:02D8:2
      005:02E2:4
      005:02E8:0
      005:02ED:2
      005:02F0:0
      005:02F2:2
      005:02F8:3
      005:02F8:3
      005:02F8:3
      005:02F8:3
      005:02FE:7
      005:0374:4
      005:037A:4
      005:0312:0
      005:0317:3
      005:0317:3
      005:0318:0
      005:031L:3
      005:031D:3
      005:031F:0
      005:0320:2
      005:0320:2
      005:0320:5
      005:0321:3
      005:0321:3
      005:0326:5
      005:0329:3
      005:032F:5
      005:0336:5
      005:033C:1
      005:0341:3
      005:0346:5
      005:034C:1
      005:034E:5
      005:0351:1
      005:0351:1
      005:0357:3
      005:0357:3
      005:035D:0
      005:0363:5
      005:0369:2
      005:036E:5
      005:0374:2

```

```

AVEFQ[1+(J DIV AVEFQ)]:=1./FREQ[J];
END UNTIL J:=*AVEFQ DEG N - 1;

CALCULATE WAVE DIRECTION AND RMS BEAM WIDTH.
IF LAV THEN BEGIN VALAVEFQ:=1; ENDP1:=60; END
ELSE BEGIN VALAVEFQ:=AVEFQ; ENDP1:=NM1; END;

K:=1;
ADDP:DO BEGIN
  IF LAV THEN J:=K ELSE J:=1 + K DIV AVEFQ;
  C11:=PSA[1,K]; C33:=PSA[3,K]; C44:=PSA[4,K];
  C34:=CNW[K]; Q13:=QSN[K]; C14:=QSN[K];
  C14:=CSN[K]; C13:=CSN[K]; Q34:=QNW[K];
  JACOBK:=JACOB[K]; K11:=KON[K]; K22:=KTW[K];
  IF (13 NEQ 0. THEN ZETA:=ARCTAN2( Q14, -Q13)
  ELSE ZETA:=SIGN(-J14)*PI/2;
  ZETA:=* 180./PI;
  ZETA IS THE DIRECTION OF PROPAGATION WRT N-W COORDINATES.
  BETA IS THE DIRECTION FROM WHICH THE WAVES ARE COMING DEG. T.
  BETA[J]:=180. - ZETA;
  K2:=(K1:=.0472840946*(FSTEP*K)**2)**2;
  * PI**2/GEE = .0472840946.
  IF C11 NEQ 0. THEN
    KR:=SQRT((C33 - C44)**2 + 4.*C34**2)/(K2*C11) ELSE KR:=0.;
    ALL[J]:=KR;
    C:=(1. - KR)/(1. + KR); IF C LSS 0. THEN C:=0.;
    C:=2.*ARCTAN(SQRT(C));
    CREST[J]:=180.*C/PI;
  CALCULATE FOURIER COEFFICIENTS OF DIRECTION FOR EA. FREQ.
  DIRECTIONAL COEFFICIENTS ARE WRT ANGLE ZETA NOT BETA.
  A0[J]:=C11/PI;
  A1[J]:=(13/(PI*K1)); B1[J]:=Q14/(PI*K1);
  A2[J]:=(C33 - C44)/(PI*K2); B2[J]:=2.*C34/(PI*K2);

  CALCULATE SPECTRAL MOMENTS AND RATIOS OF MOMENTS ETC.
  NZERO:=C11*JACOBK; % THIS IS N00.
  N01 :=Q13*JACOBK/K11; % THIS IS N01 (QSN).
  N10 :=Q14*JACOBK/K11; % THIS IS N10 (QSE).
  N20 :=C44*JACOBK/K22; % THIS IS N20 (CO-EE).
  N02 :=C33*JACOBK/K22; % THIS IS N02 (CO-NN).
  N11 :=C34*JACOBK/K22; % THIS IS N11 (CO-NE).

  N12:=C14*JACOBK/K11; % (CO-SE) & NA6[J].
  N21:=C13*JACOBK/K11; % (CO-SN) & NA7[J].
  N22:=Q34*JACOBK/K22; % (CNE) & NA8[J].

  IF NZERO NEQ 0. THEN ANG1[J]:=ARCTAN2( N01, N10 )
  ELSE ANG1[J]:=0.;
  ANG1[J]:=* 180./PI;
  IF NZERO NEQ 0. THEN
    ANG2[J]:=5.*ARCTAN2( 2.*N11, (N20 - N02) ) ELSE
    ANG2[J]:=0.;
  ANG2[J]:=* 180./PI;

  DENOM1:=N10**2 + N01**2;
  IF DENOM1 NEQ 0. THEN
    RNEW[J]:=(N10*(N20 - N02) + 2.*N01*N11)/DENOM1 ELSE

```

```

RNEW[J]:=0.;
NNN[J]:=(2. + 4.*RNEW[J]/PI)/(1. - RNEW[J]/PI);
DENOM2:=SQRT(DENOM1);
IF LENG2 GT 0. AND NNN[J] NEQ 0. THEN
  XALPH[J]:=NZERO/(2.*PI*DENOM2) - (NNN[J]*2.)/NNN[J] ELSE
  XALPH[J]:=0.;
NA1[J]:=N01; NA2[J]:=N10; NA3[J]:=N20; NA4[J]:=N02;
NA5[J]:=N11; NA6[J]:=N12; NA7[J]:=N21; NA8[J]:=N22;
IF NZERO EQL 0. THEN BEGIN
  NA1[J]:=0.; NA2[J]:=0.; NA3[J]:=0.; NA4[J]:=0.; NA5[J]:=0.;
  NA6[J]:=0.; NA7[J]:=0.; NA8[J]:=0.;
END ELSE BEGIN
  NOTE: THE RATIO OF THE AVERAGE MOMENTS ARE COMPUTED, NOT THE
  AVERAGE RATIO.
  NA1[J]:=**/NZERO; NA2[J]:=**/NZERO; NA3[J]:=**/NZERO;
  NA4[J]:=**/NZERO; NA5[J]:=**/NZERO;
  NA6[J]:=**/NZERO; NA7[J]:=**/NZERO; NA8[J]:=**/NZERO;
END;
END UNTIL K:=* + VALAVEFQ GEQ ENDPT;
IF (LAV AND ENDPT EQL 65) THEN BEGIN
  K:=ENDPT; VALAVEFQ:=* * 2; ENLPT:=128; END ELSE
IF LAV THEN BEGIN K:=ENDPT+1; VALAVEFQ:=* * 2; ENLPT:=* * 2; END;
IF (LAV AND ENLPT LEQ NM1) THEN GO TO AIDIR;
K:=1; WEST:=1;
WHILE AVEPER[K] GT .985 DO BEGIN WEST:=*+AVEFQ; K:=*+1; END;
A .985 SEC. PERIOD WAVE HAS A WAVELENGTH EQL BUOY DIA.=5 FT.
WEST:=NM1; * 10 PRINT OUT ALL VALUE UP TO NYQUIST.
IF TABLE1 THEN WRITE(PRINTER(SKIP 1));
IF TABLE2 THEN BEGIN
  WRITE(PRINTER,"NORMALIZED AND AVERAGED CROSS SPECTRA",/);
  WRITE(PRINTER,F9); WRITE(PRINTER,F10); WRITE(PRINTER,F11);
  WRITE(PRINTER,F15);
  K:=1;
  IF LAV THEN BEGIN VALAVEFQ:=1; ENDPT:=65;
  TAB2:WRITE(PRINTER,F12,DO [2.*PI*FREQ[K],AVEPER[K],
    PS[K],PSA[1,K],PSA[3,K],PSA[4,K],CSW[K],QSN[K],CSW[K],QSW[K],
    CNW[K],QNW[K],BETA[K],CREST[K]] UNTIL K:=*+VALAVEFQ GEQ
    ENDPT);
  IF ENLPT EQL 65 THEN BEGIN K:=65; VALAVEFQ:=* * 2; ENLPT:=128;
  END ELSE BEGIN K:=ENLPT+1; VALAVEFQ:=* * 2; ENLPT:=* * 2; END;
  IF ENLPT LEQ NM1 THEN GO TO TAB2;
END ELSE
  WRITE(PRINTER,F12,DO [2.*PI*FREQ[K],AVEPER[1+(K DIV AVEFQ)],
    PS[K],PSA[1,K],PSA[3,K],PSA[4,K],CSW[K],QSN[K],CSW[K],QSW[K],
    CNW[K],QNW[K],BETA[1+(K DIV AVEFQ)],CREST[1+(K DIV AVEFQ)]]
  UNTIL K:=* + AVEFQ GEQ WEST);
END;
IF ((TABLE2 AND TABLE3) OR (TABLE1 AND TABLE3)) THEN
  WRITE(PRINTER(SKIP 1));

```

```

J:=1; K:=1;
WHILE AVEPER(J) CTR TLIM DO J:=*+1;
WHILE AVEPER(K) CTR .989 DO K:=*+1;
IF TABLE3 THEN BEGIN
WRITE(PRINTER,F13,TLIM); WRITE(PRINTER,F14);
WRITE(PRINTER,F5);
IF (NOT LAV) THEN
WRITE(PRINTER,F8, DO [J,AVEPER(J),A0(J),A1(J),A2(J),
B1(J),B2(J),BETA(J),CREST(J)] UNTIL J:=*+1 GEQ K)
ELSE BEGIN
VALAVEFQ:=1; ENDPT:=65;
TAB3:WRITE(PRINTER,F8,DO [J,AVEPER(J),A0(J),A1(J),A2(J),B1(J),B2(J),
BETA(J),CREST(J)] UNTIL J:=*+VALAVEFQ GEQ ENDPT);
IF ENDPT EQL 65 THEN BEGIN J:=65; VALAVEFQ:=* * 2; ENDPT:=128;
END ELSE BEGIN
J:=ENDPT+1; VALAVEFQ:=* * 2; ENDPT:=* * 2; END;
IF ENDPT LEQ NM1 THEN GO TO TAB3;
END;
%FOR TABLE 4 THERE IS AN UNCONDITIONAL PRINT.
WRITE(PRINTER(SKIP 1));
WRITE(PRINTER,F16); K:=1;
WRITE(PRINTER,F17,DO [2.*PI*FREQ(K),NA1[1+K DIV AVEFQ],
NA2[1+K DIV AVEFQ],
NA3[1+K DIV AVEFQ],NA4[1+K DIV AVEFQ],NA5[1+K DIV AVEFQ],
ANG1[1+K DIV AVEFQ],ANG2[1+K DIV AVEFQ],RNEW[1+K DIV AVEFQ],
RLD[1+K DIV AVEFQ],
NNN[1+K DIV AVEFQ],XALPH[1+K DIV AVEFQ]] UNTIL K:=*+AVEFQ
GEQ NM1);
%
%
TABLE 5 IS ALSO AN UNCONDITIONAL PRINT.
WRITE(PRINTER(SKIP 1));
WRITE(PRINTER,<"THESE MOMENT RATIOS SHOULD BE SMALL; NCHECK=",
"NO1 + NO (SHOULD EQL 1.0).",/;>);
WRITE(PRINTER,F18); K:=1;
WRITE(PRINTER,F19,DO [2.*PI*FREQ(K),NA6[1+K DIV AVEFQ],
NA7[1+K DIV AVEFQ],NA8[1+K DIV AVEFQ],
NA1[1+K DIV AVEFQ] + NA2[1+K DIV AVEFQ]]
UNTIL K:=*+AVEFQ GEQ NM1);
%
IF PUNCH5 THEN BEGIN
J:=1;
IF (NOT LAV) THEN
WRITE(PUNCHER,<BE10.2>, DO [CSN(J),QSN(J),CSW(J),QSW(J),CNW(J),
QNW(J),PS(J),FREQ(J)] UNTIL J:=*+AVEFQ GEQ NM1)
ELSE BEGIN
VALAVEFQ:=1; ENDPT:=65;
FUN1:WRITE(PUNCHER,<BE10.2>, DO [CSN(J),QSN(J),CSW(J),QSW(J),CNW(J),
QNW(J),PS(J),FREQ(J)] UNTIL J:=*+VALAVEFQ GEQ ENDPT);
IF ENDPT EQL 65 THEN BEGIN J:=65; VALAVEFQ:=* * 2; ENDPT:=128;
END ELSE BEGIN
J:=ENDPT+1; VALAVEFQ:=* * 2; ENDPT:=* * 2; END;
IF ENDPT LEQ NM1 THEN GO TO FUN1;
END;
IF PUNCH5 THEN BEGIN
IF (NOT LAV) THEN BEGIN
J:=1;WRITE(PUNCHER,<BE10.2>,DO PSA[1,J] UNTIL J:=*+AVEFQ GEQ NM1);
J:=1;WRITE(PUNCHER,<BE10.2>,DO PSA[3,J] UNTIL J:=*+AVEFQ GEQ NM1);
J:=1;WRITE(PUNCHER,<BE10.2>,DO PSA[4,J] UNTIL J:=*+AVEFQ GEQ NM1);
END ELSE BEGIN
FOR K:=1, 3, 4 DO BEGIN
VALAVEFQ:=1; ENDPT:=65; J:=1;
FUN2:WRITE(PUNCHER,<BE10.2>,DO PSA[K,J] UNTIL J:=*+VALAVEFQ GEQ ENDPT);
IF ENDPT EQL 65 THEN BEGIN J:=65; VALAVEFQ:=* * 2; ENDPT:=128;
END ELSE BEGIN
J:=ENDPT+1; VALAVEFQ:=* * 2; ENDPT:=* * 2; END;
IF ENDPT LEQ NM1 THEN GO TO FUN2;
END;
IF PUNCH5 THEN BEGIN
IF (NOT LAV) THEN BEGIN
K:=NM1 DIV AVEFQ;
J:=1;WRITE(PUNCHER,<BE10.2>,DO [FREQ[1+(J-1)*AVEFQ],BETA(J),
CREST(J),A0(J),A1(J),A2(J),B1(J),B2(J)] UNTIL J:=*+1 GEQ K);
END ELSE BEGIN
VALAVEFQ:=1; ENDPT:=65; J:=1;
FUN3:WRITE(PUNCHER,<BE10.2>, DO [FREQ(J),BETA(J),
CALOT(J),A0(J),A1(J),A2(J),B1(J),B2(J)] UNTIL J:=*+VALAVEFQ GEQ
ENDPT);
IF ENDPT EQL 65 THEN BEGIN J:=65; VALAVEFQ:=* * 2; ENDPT:=128;
END ELSE BEGIN
J:=ENDPT+1; VALAVEFQ:=* * 2; ENDPT:=* * 2; END;
IF ENDPT LEQ NM1 THEN GO TO FUN3;
END;
FINI:END; % END OF MAIN BLOCK.

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005:04FB:0

005:04FE:3

005:0503:3

005:0514:2

005:0517:4

005:051D:0

005:051D:2

005:051E:5

005:053D:2

005:0543:0

005:0544:3

005:055E:5

005:0569:4

005:056E:1

005:058E:4

005:0573:0

005:0574:2

005:0574:2

005:0574:2

005:0573:3

005:057F:4

005:058E:4

005:058E:4

005:059C:4

005:059C:4

005:05A7:1

005:05AA:4

005:05B2:2

005:05B8:4

005:05B8:4

005:05B8:4

005:05B8:4

005:05B8:4

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## COMPONENTS

The following is a list of the major components of the buoy, procurement source, and approximate cost in 1972.

1. Battery: Lead-Acid 12 volts, 20 ampere hour capacity (6 required) \$40 ea  
Model GC12200  
Globe Battery Division  
P.O. Box 591  
Milwaukee, Wisconsin 53201
2. Inverter: 12 VDC to 115 VAC 400 Hz 100 watt capacity \$250  
Model 12400-12(w/input-output filters)  
Nova Electric Manufacturing Co.  
263 Hillside Ave.  
Nutley, New Jersey 07100
3. Radio Transmitter: Citizen band (Marine data channels) \$150  
500 mw, modulated  
Model BT-109 (modified)  
Ocean Applied Research Corp.  
10475 Roselle Street  
San Diego, California 92121
4. Visual Beacon: Flashing Xenon Lamp \$200  
0.5 flashes/sec, self contained batteries  
Model  
Ocean Applied Research Corp.  
10475 Roselle Street  
San Diego, California 92121

5. Vertical Gyro/Accelerometer Assy: Includes Honeywell \$6000  
Model GG326C1 Quartz fiber accelerometer  
mounted on inner gimbal of Honeywell Model  
JG7044A45 vertical accelerometer  
Model GG1134AA01  
Honeywell Inc. Aerospace Division Dept 691  
2600 Ridgeway Rd.  
Minneapolis, Minnesota 55413
6. Directional Gyroscope: North seeking \$700  
Model DG04-0122-1  
Humphrey, Inc.  
9212 Balboa St.  
San Diego, California
7. Data Recorder System \$4000
- A. Data Recorder/Logic Assembly  
Model 10015  
Monitor Labs, Inc.  
10451 Roselle St.  
San Diego, California 92121
- B. Incremental Digital Tape Recorder \$2500  
Model 1387  
Precision Instrument Co.  
3170 Porter Drive  
Palo Alto, California

- C. Low-Power Analog-to-Digital Converter \$900  
Model ADC-12QL  
Analog Devices, Inc.  
P.O. Box 280  
Norwood, Mass. 02062
- D. Low-drift, low-power operational amplifier \$50  
Model 153J  
Analog Devices, Inc.  
P.O. Box 280  
Norwood, Mass. 02062
8. Buoy Hull Assy \$10,000  
No Part Number  
Honeywell Marine Systems Center  
5303 Shilshole Ave., N.W.  
Seattle, Washington 98107
9. Radio Transmitter Antenna: 3 needed \$75 ea  
Model AW257  
Ocean Applied Research Corp.  
10475 Roselle St.  
San Diego, Ca. 92121